US010036931B2

(12) United States Patent
Chan et al.

(10) Patent No.: US 10,036,931 B2
(45) Date of Patent: Jul. 31, 2018

(54) **COLOR DISPLAY DEVICE**

(71) Applicant: **E Ink California, LLC.**, Fremont, CA (US)

(72) Inventors: **Bryan Hans Chan**, San Francisco, CA (US); **Craig Lin**, Oakland, CA (US); **Hui Du**, Milpitas, CA (US); **HongMei Zang**, Fremont, CA (US)

(73) Assignee: **E INK CALIFORNIA, LLC**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/337,272**

(22) Filed: **Oct. 28, 2016**

(65) **Prior Publication Data**

US 2017/0045798 A1 Feb. 16, 2017

Related U.S. Application Data

(63) Continuation of application No. 14/596,160, filed on Jan. 13, 2015, now Pat. No. 9,513,527.

(60) Provisional application No. 61/927,418, filed on Jan. 14, 2014.

(51) **Int. Cl.**

G02B 26/00	(2006.01)
G09G 3/34	(2006.01)
G02F 1/167	(2006.01)
G02F 1/133	(2006.01)

(52) **U.S. Cl.**

CPC ***G02F 1/167*** (2013.01); ***G02F 1/13306*** (2013.01); ***G09G 3/344*** (2013.01); *G02F 2001/1678* (2013.01); *G02F 2203/34* (2013.01)

(58) **Field of Classification Search**

CPC . G02F 1/167; G02F 2001/1678; G09G 3/344; G09F 9/372

USPC 359/296; 345/107; 430/32; 204/600

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,756,693	A	9/1973	Ota
3,892,568	A	7/1975	Ota
4,298,448	A	11/1981	Muller
5,378,574	A	1/1995	Winnik
5,980,719	A	11/1999	Cherukuri
6,017,584	A	1/2000	Albert
6,198,809	B1	3/2001	Disanto
6,337,761	B1	1/2002	Rogers
6,373,461	B1	4/2002	Hasegawa
6,486,866	B1	11/2002	Kuwahara et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CN	1705907	12/2005
JP	2006343458	12/2006

(Continued)

OTHER PUBLICATIONS

Seigou Kawaguchi, et al (2000) Synthesis of polyethylene macromonomers and their radical copolymerizations with methyl methacrylate in homogeneous and oligoethylene melts media. Designed Monomers and Polymers 2000, vol. 3, No. 3, pp. 263-277.

(Continued)

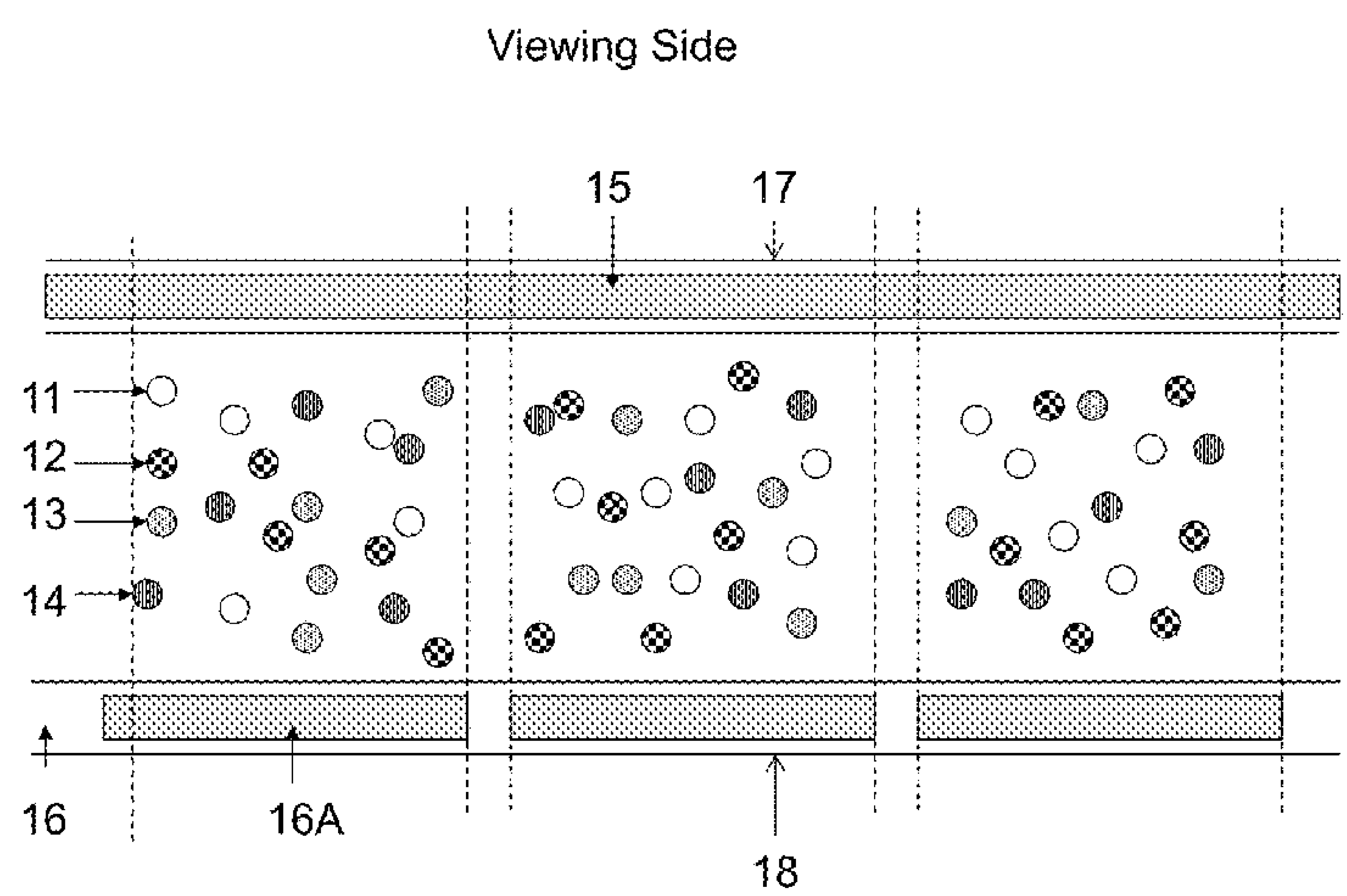
Primary Examiner — William Choi

(74) *Attorney, Agent, or Firm* — Brian D. Bean

(57) **ABSTRACT**

The present invention provides a full color display device in which each pixel can display multiple high-quality color states. More specifically, an electrophoretic fluid is provided which comprises four types of particles, dispersed in a solvent or solvent mixture and each pixel can display at least five different color states.

14 Claims, 16 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

6,517,618	B2	2/2003	Foucher
6,525,866	B1	2/2003	Lin
6,538,801	B2	3/2003	Jacobson
6,545,797	B2	4/2003	Chen
6,600,534	B1	7/2003	Tanaka
6,650,462	B2	11/2003	Katase
6,664,944	B1	12/2003	Albert
6,680,726	B2	1/2004	Gordon, II
6,693,620	B1	2/2004	Herb
6,704,133	B2	3/2004	Gates
6,724,521	B2	4/2004	Nakao
6,729,718	B2	5/2004	Goto
6,751,007	B2	6/2004	Liang
6,751,008	B2	6/2004	Liang
6,781,745	B2	8/2004	Chung
6,788,452	B2	9/2004	Liang
6,829,078	B2	12/2004	Liang
6,850,357	B2	2/2005	Kaneko
6,864,875	B2	3/2005	Drzaic
6,876,486	B2	4/2005	Hiraoka
6,914,714	B2	7/2005	Chen
6,930,818	B1	8/2005	Liang
6,947,203	B2	9/2005	Kanbe
6,967,762	B2	11/2005	Machida
6,972,893	B2	12/2005	Chen et al.
6,987,503	B2	1/2006	Inoue
6,987,605	B2	1/2006	Liang
7,009,756	B2	3/2006	Kishi
7,019,889	B2	3/2006	Katase
7,034,987	B2	4/2006	Schlangen
7,038,655	B2	5/2006	Herb
7,038,656	B2	5/2006	Liang
7,038,670	B2	5/2006	Liang
7,046,228	B2	5/2006	Liang
7,050,218	B2	5/2006	Kanbe
7,052,571	B2	5/2006	Wang
7,057,600	B2	6/2006	Goden
7,057,798	B2	6/2006	Ukigaya
7,075,502	B1	7/2006	Drzaic
7,116,466	B2	10/2006	Whitesides et al.
7,167,155	B1	1/2007	Albert et al.
7,226,550	B2	6/2007	Hou
7,259,744	B2	8/2007	Arango
7,271,947	B2	9/2007	Liang
7,283,119	B2	10/2007	Kishi
7,292,386	B2	11/2007	Kanbe
7,303,818	B2	12/2007	Minami
7,304,987	B1	12/2007	James
7,312,916	B2	12/2007	Pullen
7,342,556	B2	3/2008	Oue
7,345,810	B2	3/2008	Chopra
7,352,353	B2	4/2008	Albert
7,365,732	B2	4/2008	Matsuda
7,382,351	B2	6/2008	Kishi
7,385,751	B2	6/2008	Chen
7,411,719	B2	8/2008	Paolini, Jr. et al.
7,417,787	B2	8/2008	Chopra
7,420,549	B2	9/2008	Jacobson
7,433,113	B2	10/2008	Chopra
7,443,570	B2	10/2008	Chopra
7,474,295	B2	1/2009	Matsuda
7,492,505	B2	2/2009	Liang
7,495,821	B2	2/2009	Yamakita
7,502,162	B2	3/2009	Lin
7,545,557	B2	6/2009	Iftime
7,548,291	B2	6/2009	Lee
7,557,981	B2	7/2009	Liang
7,580,025	B2	8/2009	Nakai
7,605,972	B2	10/2009	Kawai
7,609,435	B2	10/2009	Moriyama
7,626,185	B2	12/2009	Krak
7,636,076	B2	12/2009	Hung
7,652,656	B2	1/2010	Chopra
7,656,576	B2	2/2010	Suwabe
7,667,684	B2	2/2010	Jacobson et al.
7,679,599	B2	3/2010	Kawai
7,684,108	B2	3/2010	Wang
7,686,463	B2	3/2010	Goto
7,760,419	B2	7/2010	Lee
7,782,292	B2	8/2010	Miyasaka
7,791,789	B2	9/2010	Albert
7,800,813	B2	9/2010	Wu
7,808,696	B2	10/2010	Lee
7,821,702	B2	10/2010	Liang
7,830,592	B1	11/2010	Sprague
7,839,564	B2	11/2010	Whitesides et al.
7,848,009	B2	12/2010	Machida
7,852,547	B2	12/2010	Kim
7,852,548	B2	12/2010	Roh
7,907,327	B2	3/2011	Jang
7,910,175	B2	3/2011	Webber
7,911,681	B2	3/2011	Ikegami
7,952,790	B2	5/2011	Honeyman
7,956,841	B2	6/2011	Albert
7,982,941	B2	7/2011	Lin
8,040,594	B2	10/2011	Paolini, Jr.
8,054,526	B2	11/2011	Bouchard
8,067,305	B2	11/2011	Zafiropoulo
8,072,675	B2	12/2011	Lin
8,081,375	B2	12/2011	Komatsu
8,089,686	B2	1/2012	Addington
8,098,418	B2	1/2012	Paolini, Jr.
8,115,729	B2	2/2012	Danner
8,120,838	B2	2/2012	Lin
8,159,636	B2	4/2012	Sun
8,164,823	B2	4/2012	Ikegami
8,169,690	B2	5/2012	Lin
8,174,492	B2	5/2012	Kim
8,213,076	B2	7/2012	Albert
8,237,892	B1	8/2012	Sprague
8,243,013	B1	8/2012	Sprague
8,355,196	B2	1/2013	Yan
8,363,299	B2	1/2013	Paolini, Jr.
8,395,836	B2	3/2013	Lin
8,422,116	B2	4/2013	Sprague
8,441,713	B2	5/2013	Kawashima
8,441,714	B2	5/2013	Paolini, Jr.
8,441,716	B2	5/2013	Paolini, Jr.
8,466,852	B2	6/2013	Drzaic
8,477,404	B2	7/2013	Moriyama
8,477,405	B2	7/2013	Ishii
8,503,063	B2	8/2013	Sprague
8,520,296	B2	8/2013	Wang
8,537,104	B2	9/2013	Markvoort
8,565,522	B2	10/2013	Swic
8,570,272	B2	10/2013	Hsieh
8,570,639	B2	10/2013	Masuzawa
8,574,937	B2	11/2013	Shi
8,576,470	B2	11/2013	Paolini, Jr.
8,576,475	B2	11/2013	Huang
8,593,721	B2	11/2013	Albert
8,599,120	B2	12/2013	Kanou
8,605,354	B2	12/2013	Zhang
8,610,998	B2	12/2013	Baisch
8,629,832	B2	1/2014	Tanabe
8,649,084	B2	2/2014	Wang
8,670,174	B2	3/2014	Sprague
8,674,978	B2	3/2014	Komatsu
8,681,191	B2	3/2014	Yang
8,687,265	B2	4/2014	Ahn
8,704,754	B2	4/2014	Machida
8,704,756	B2	4/2014	Lin
8,717,662	B2	5/2014	Komatsu
8,717,664	B2	5/2014	Wang
8,786,935	B2	7/2014	Sprague
8,797,258	B2	8/2014	Sprague
8,797,634	B2	8/2014	Paolini, Jr.
8,797,636	B2	8/2014	Yang
8,797,637	B2	8/2014	Fujishiro
8,810,899	B2	8/2014	Sprague
8,830,559	B2	9/2014	Honeyman
8,873,129	B2	10/2014	Paolini, Jr.
8,902,153	B2	12/2014	Bouchard
8,902,491	B2	12/2014	Wang

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,917,439	B2	12/2014	Wang
8,964,282	B2	2/2015	Wang
8,976,444	B2	3/2015	Zhang
9,013,783	B2	4/2015	Sprague
9,052,564	B2	6/2015	Sprague
9,116,412	B2	8/2015	Lin
9,140,952	B2	9/2015	Sprague
9,146,439	B2	9/2015	Zhang
9,164,207	B2	10/2015	Honeyman et al.
9,170,467	B2	10/2015	Whitesides
9,170,468	B2	10/2015	Lin
9,182,646	B2	11/2015	Paolini, Jr.
9,195,111	B2	11/2015	Anseth
9,199,441	B2	12/2015	Danner
9,251,736	B2	2/2016	Lin
9,268,191	B2	2/2016	Paolini, Jr.
9,285,649	B2	3/2016	Du
9,293,511	B2	3/2016	Jacobson
9,341,916	B2	5/2016	Telfer et al.
9,360,733	B2	6/2016	Wang
9,361,836	B1	6/2016	Telfer et al.
9,383,623	B2	7/2016	Lin
9,423,666	B2	8/2016	Wang
9,460,666	B2	10/2016	Sprague
2001/0035926	A1	11/2001	Yamaguchi
2004/0085619	A1	5/2004	Wu
2007/0002008	A1	1/2007	Tam
2007/0080928	A1	4/2007	Ishii
2007/0273637	A1	11/2007	Zhou
2008/0042928	A1	2/2008	Schlangen
2008/0043318	A1	2/2008	Whitesides
2008/0048970	A1	2/2008	Drzaic
2008/0062159	A1	3/2008	Roh
2008/0117165	A1	5/2008	Machida
2008/0174531	A1	7/2008	Sah
2009/0153942	A1	6/2009	Daniel
2009/0167754	A1	7/2009	Hatta
2009/0184897	A1	7/2009	Miyamoto
2009/0225398	A1	9/2009	Duthaler
2009/0311484	A1	12/2009	McLellan
2010/0156780	A1	6/2010	Jacobson
2011/0043543	A1	2/2011	Chen
2011/0175939	A1	7/2011	Moriyama
2011/0199671	A1	8/2011	Amundson
2011/0217639	A1	9/2011	Sprague
2011/0234557	A1	9/2011	Yang
2012/0299947	A1	11/2012	Tsuda
2012/0326957	A1	12/2012	Drzaic
2013/0242378	A1	9/2013	Paolini, Jr.
2013/0278995	A1	10/2013	Drzaic
2014/0011913	A1	1/2014	Du
2014/0055840	A1	2/2014	Zang
2014/0078576	A1	3/2014	Sprague
2014/0340430	A1	11/2014	Telfer
2014/0340736	A1	11/2014	Lin
2014/0362213	A1	12/2014	Tseng
2015/0103394	A1	4/2015	Wang
2015/0118390	A1	4/2015	Rosenfeld
2015/0124345	A1	5/2015	Rosenfeld
2015/0198858	A1	7/2015	Chan
2015/0234250	A1	8/2015	Lin
2015/0241754	A1	8/2015	Du
2015/0268531	A1	9/2015	Wang
2015/0301246	A1	10/2015	Zang
2016/0011484	A1	1/2016	Chan
2016/0026062	A1	1/2016	Zhang
2016/0048054	A1	2/2016	Danner
2016/0116816	A1	4/2016	Paolini
2016/0116818	A1	4/2016	Du
2016/0140909	A1	5/2016	Lin
2016/0260372	A1	9/2016	Wang

FOREIGN PATENT DOCUMENTS

JP	2007033710	2/2007
JP	2008033000	2/2008
JP	2008209589	9/2008
JP	2009116041	5/2009
JP	2009192637	8/2009
JP	2009244635	10/2009
JP	2011158783	8/2011
KR	1020070082680	8/2007
KR	1020110103765	9/2011
TW	201122697	7/2011
TW	201237529	9/2012
WO	1999053373	10/1999

OTHER PUBLICATIONS

PCT/US2015/011237, PCT Notification of Transmittal of The International Search Report and The Written Opinion of The International Searching Authority, or The Declaration, dated Apr. 10, 2015.

European Patent Office; EP Appl. No. 15737734.2; Extended European Search Report; dated Jun. 6, 2017, Jun. 6, 2017.

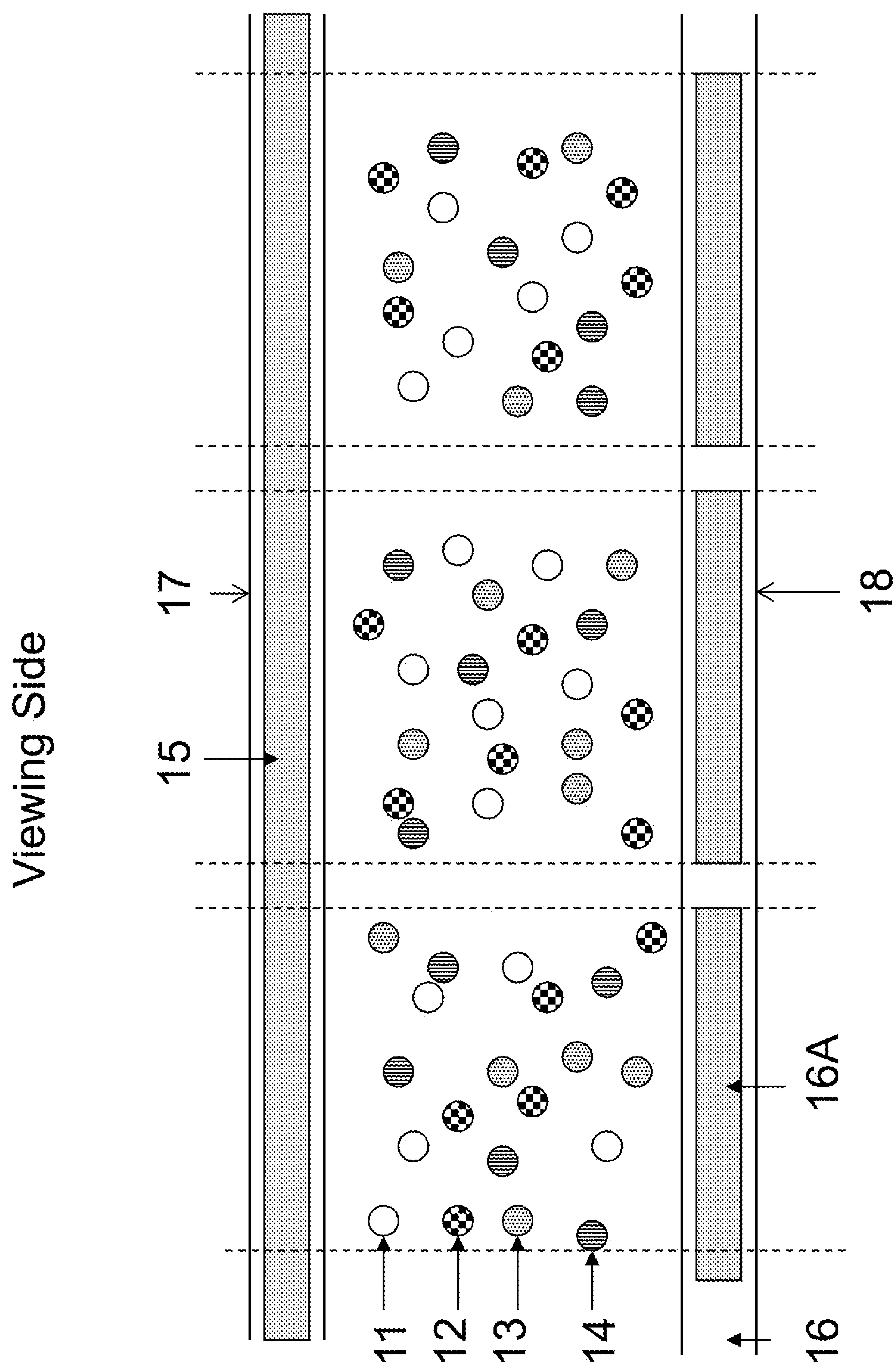


Figure 1

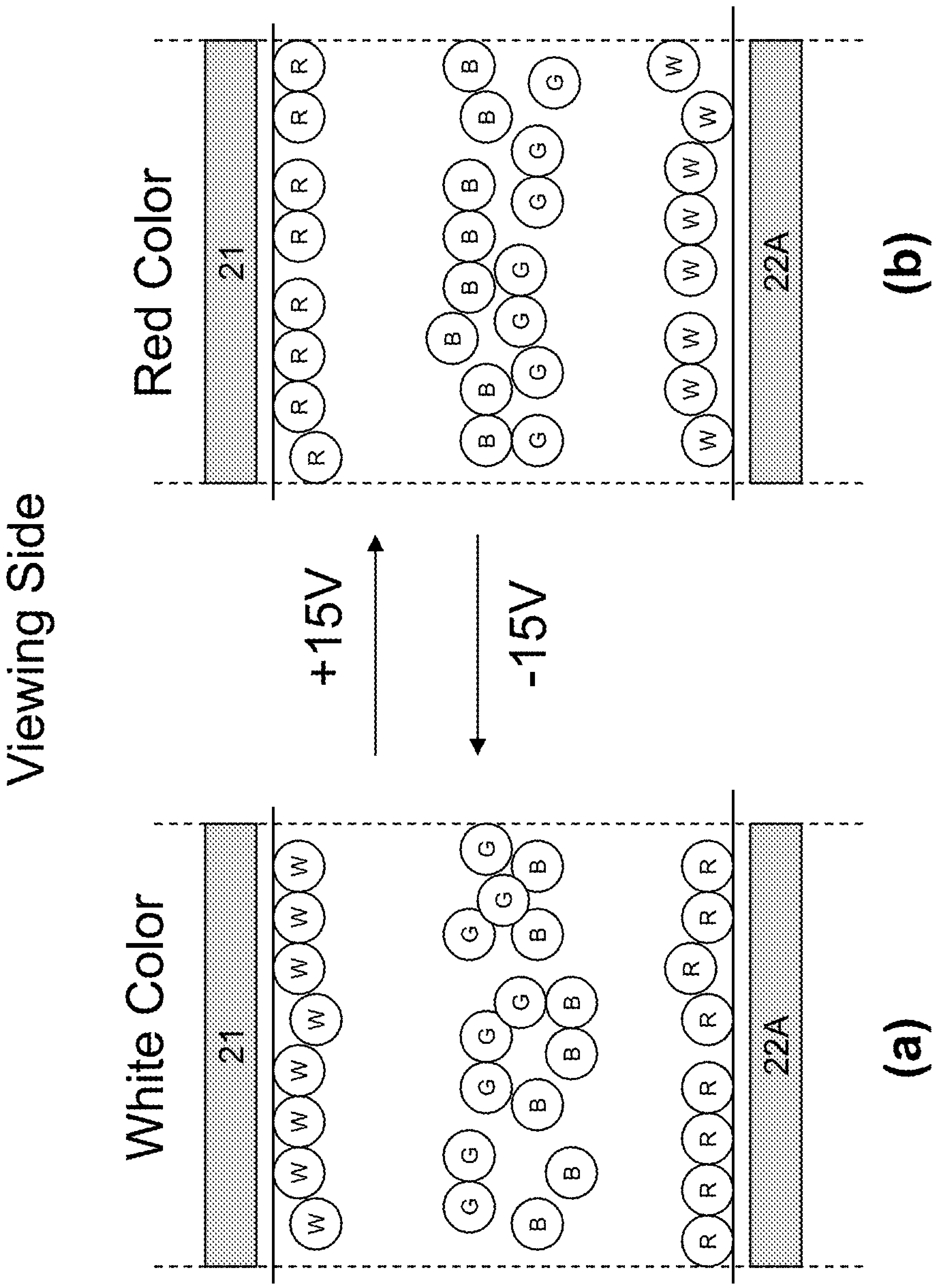


Figure 2-1

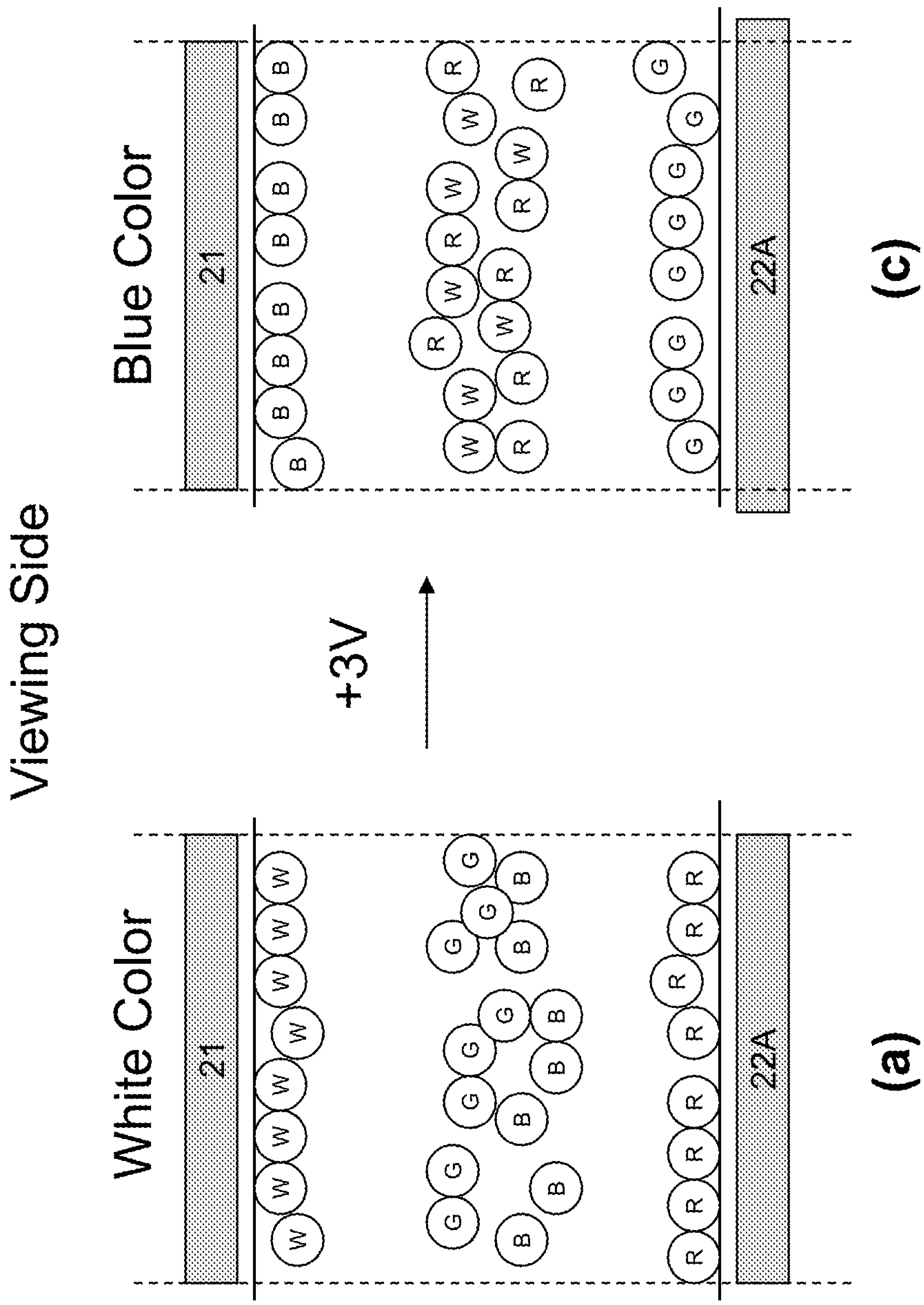


Figure 2-2

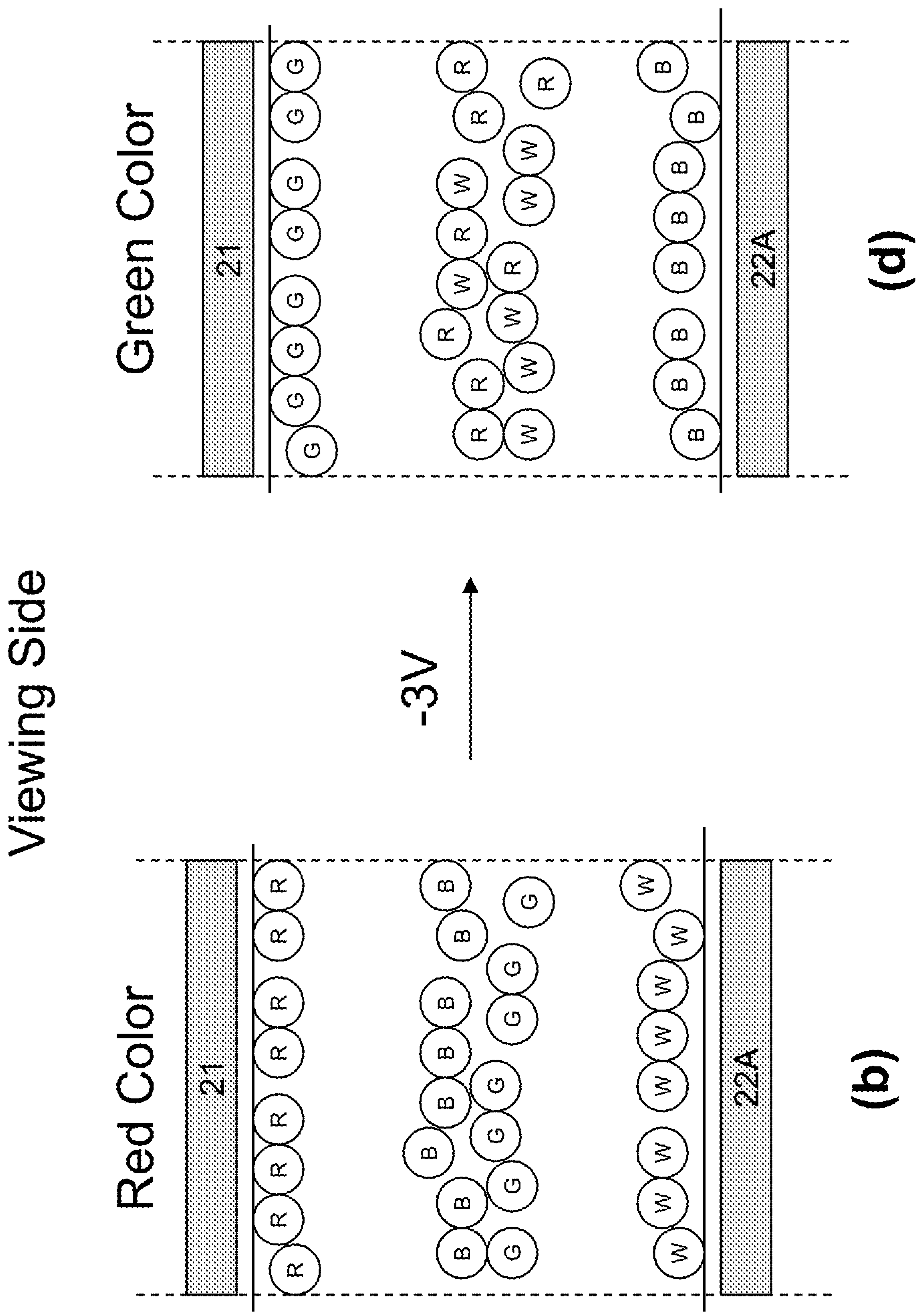


Figure 2-3

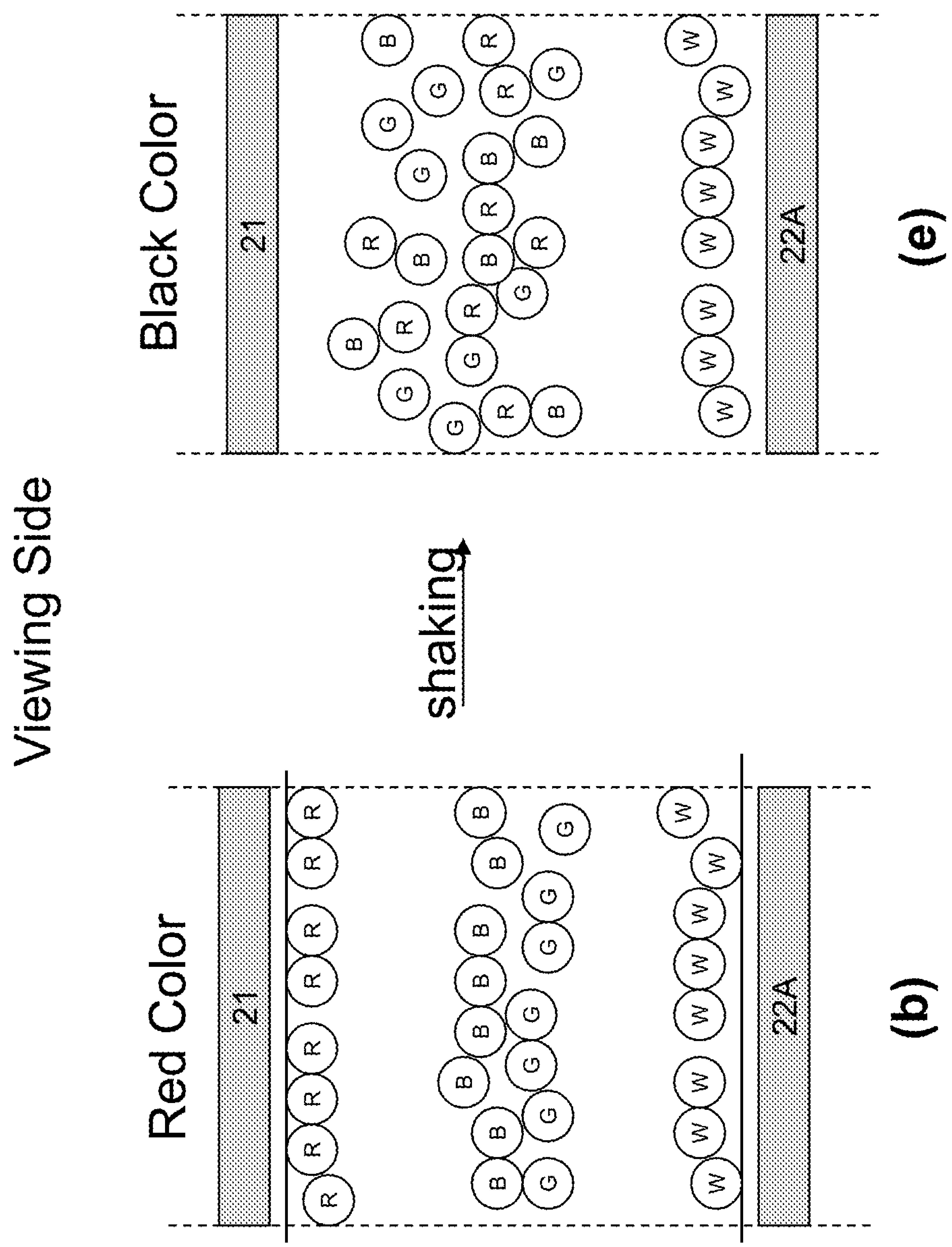


Figure 2-4

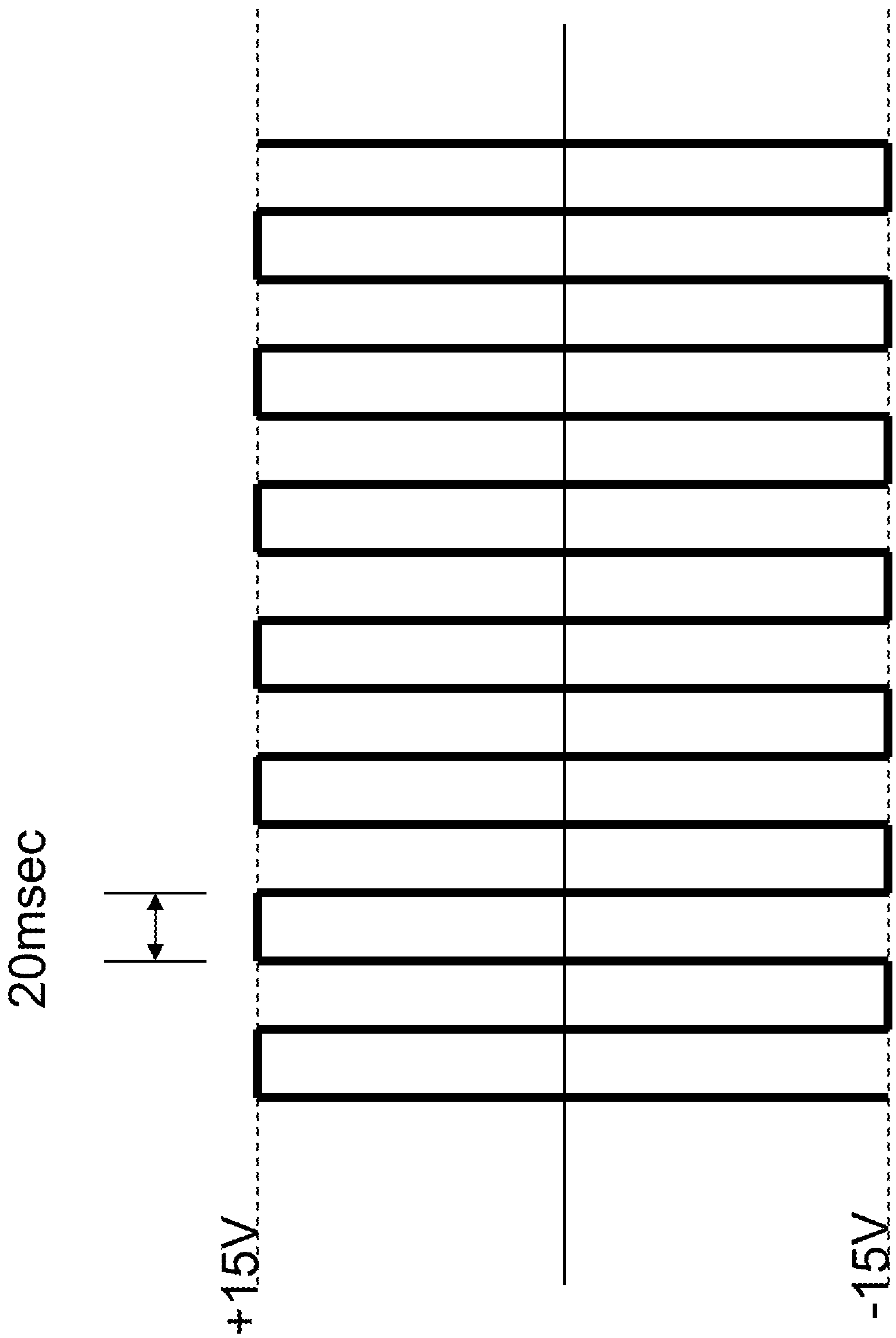


Figure 3

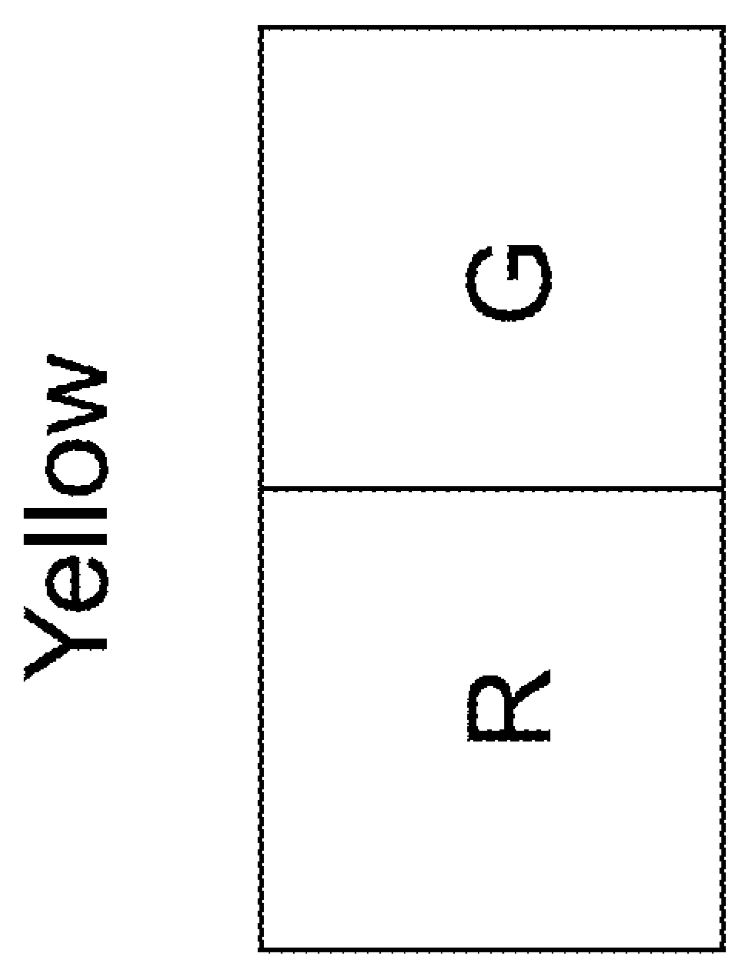


Fig. 4A

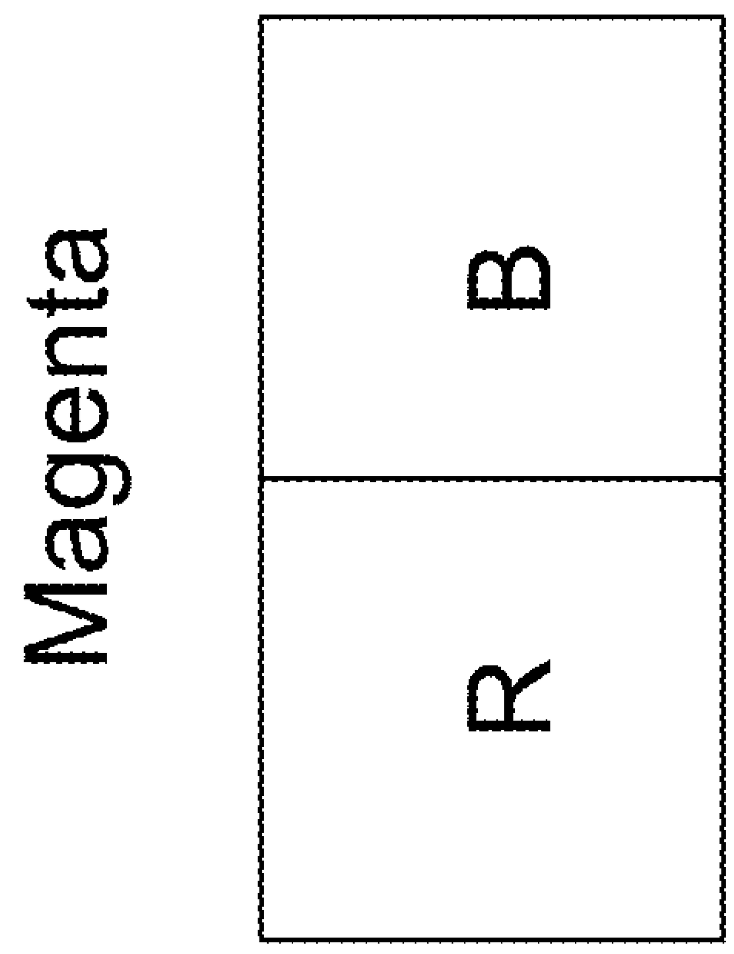


Fig. 4B

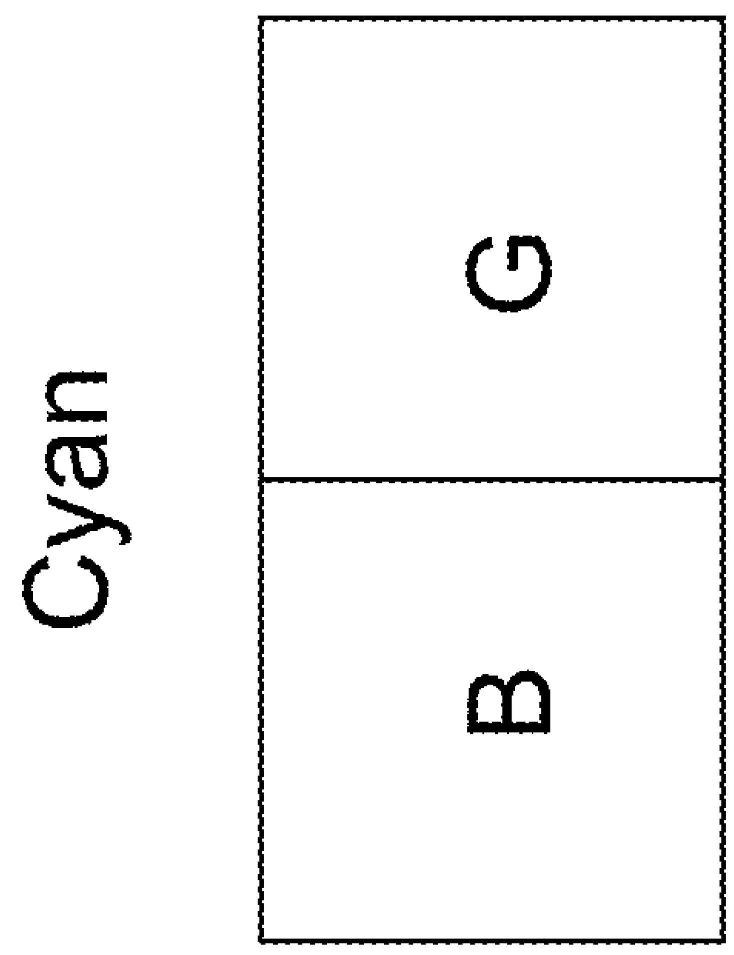


Fig. 4C

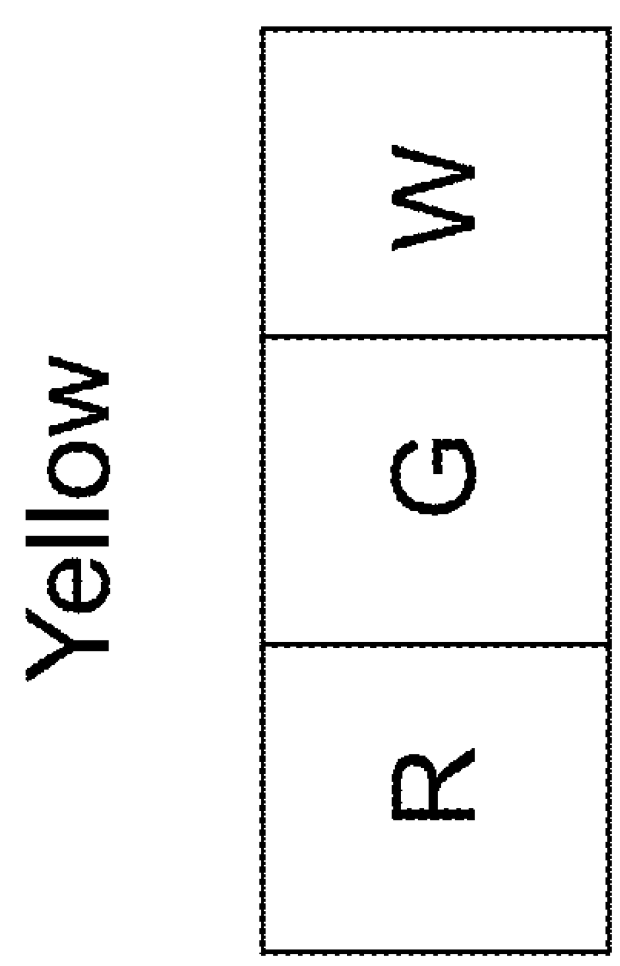


Fig. 5A

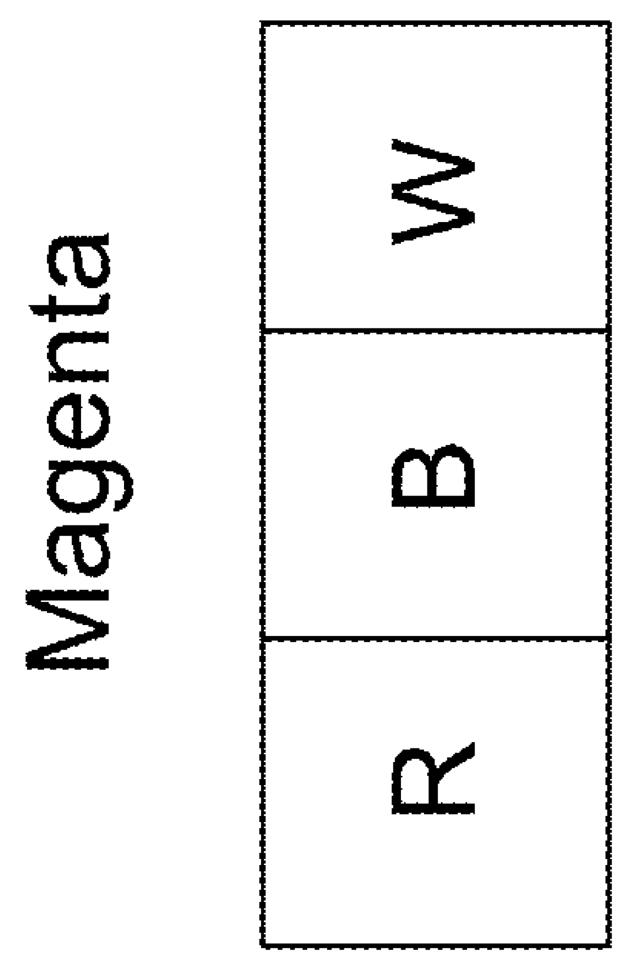


Fig. 5B

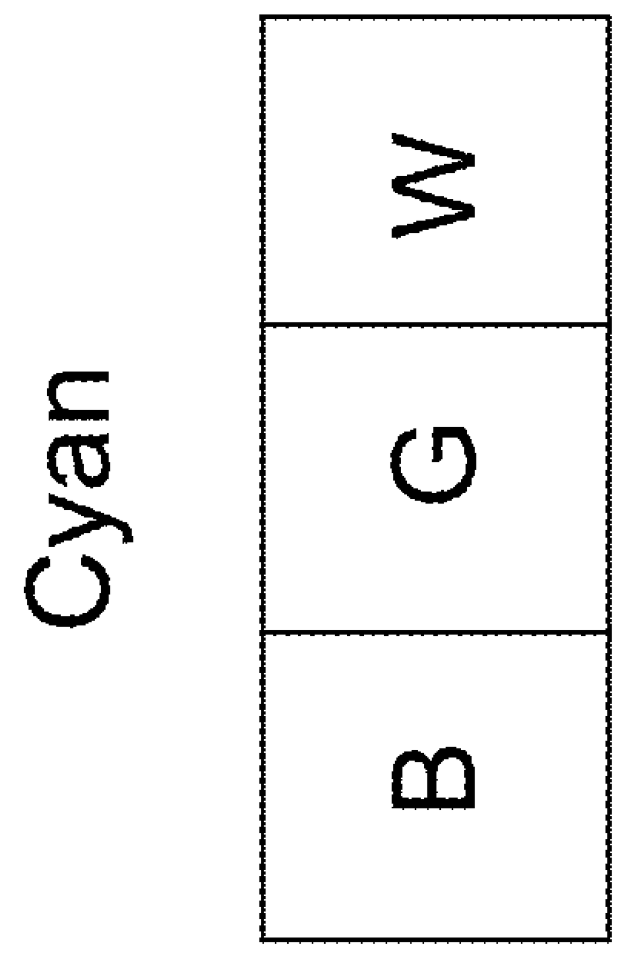


Fig. 5C

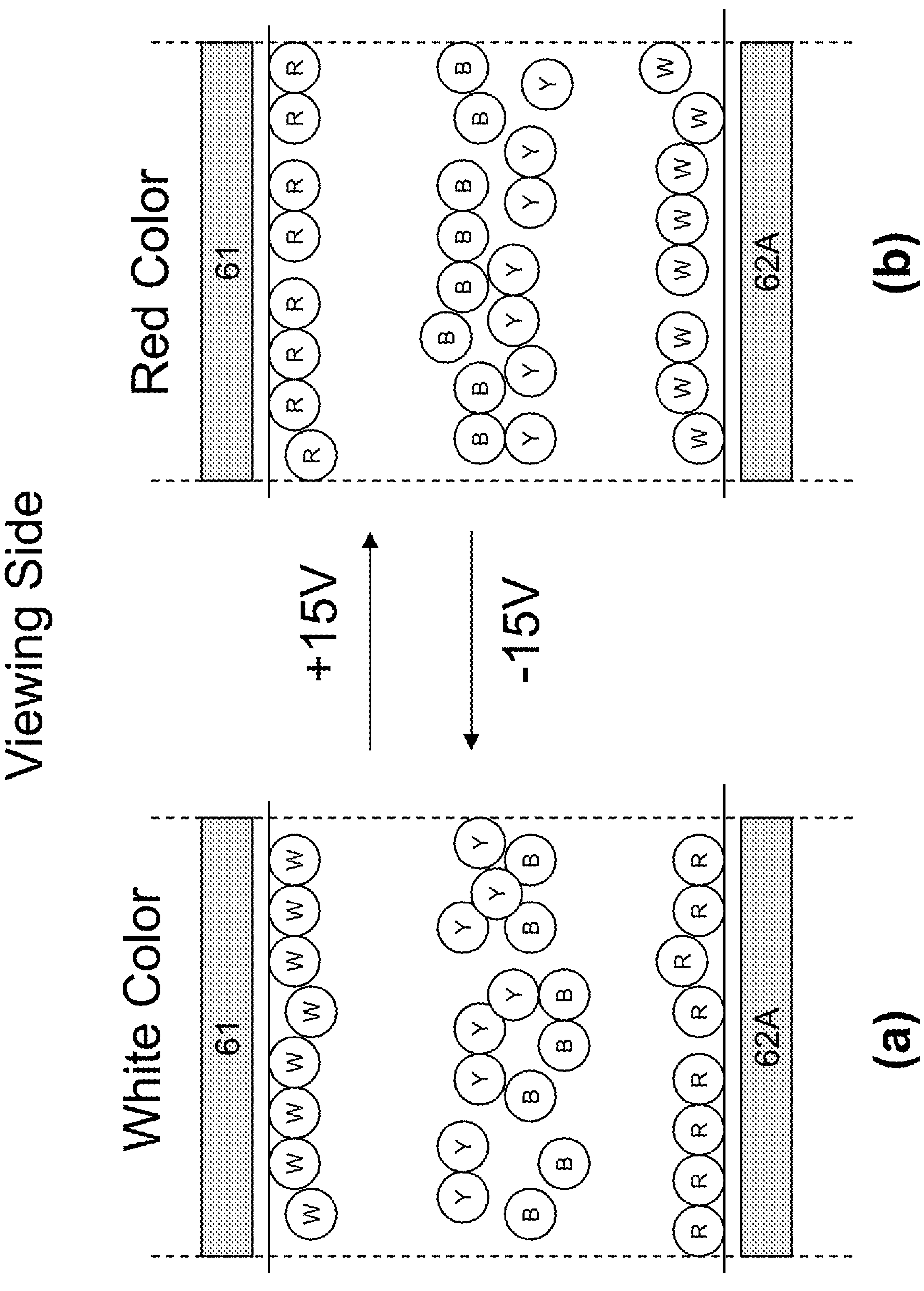


Figure 6-1

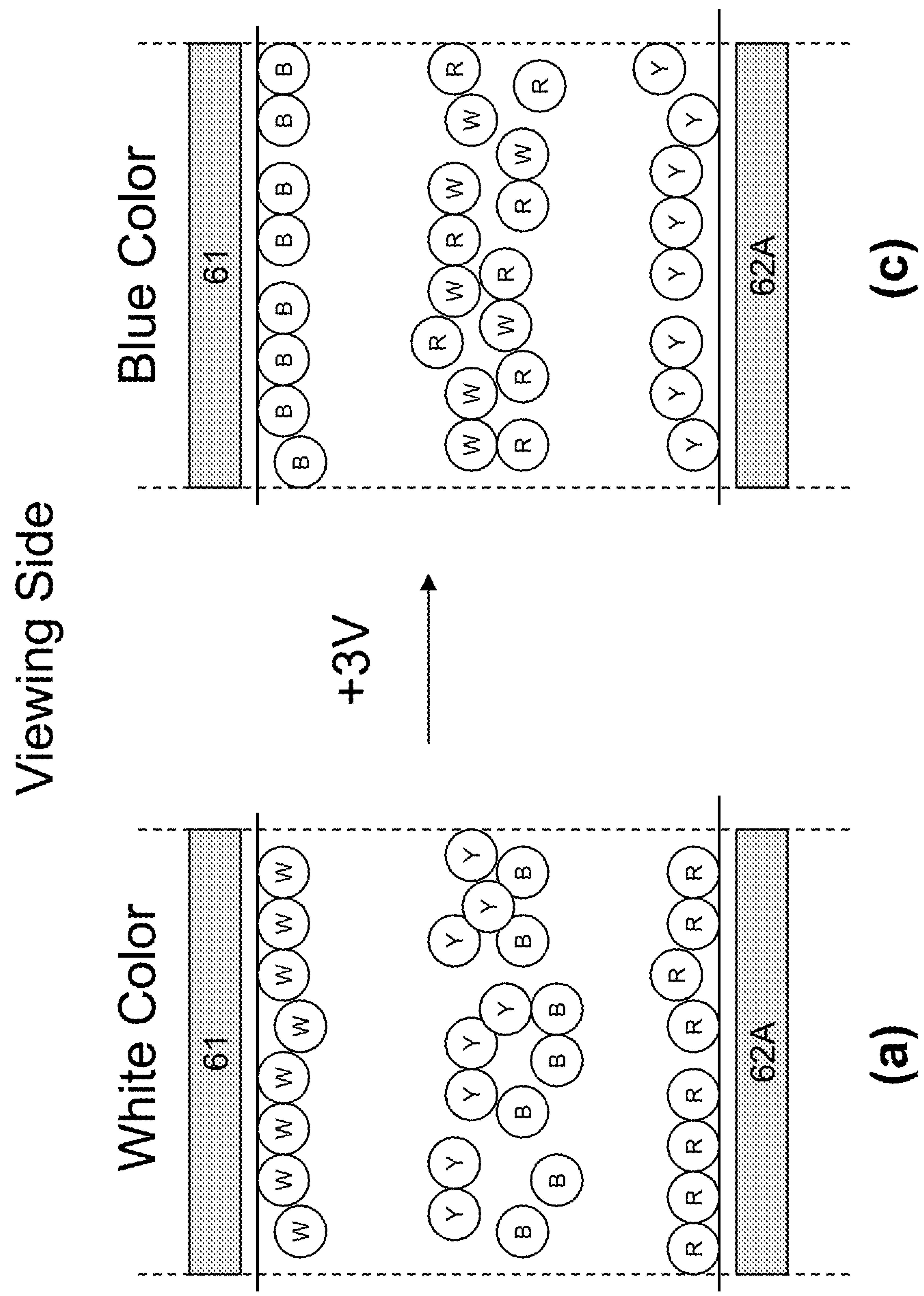


Figure 6-2

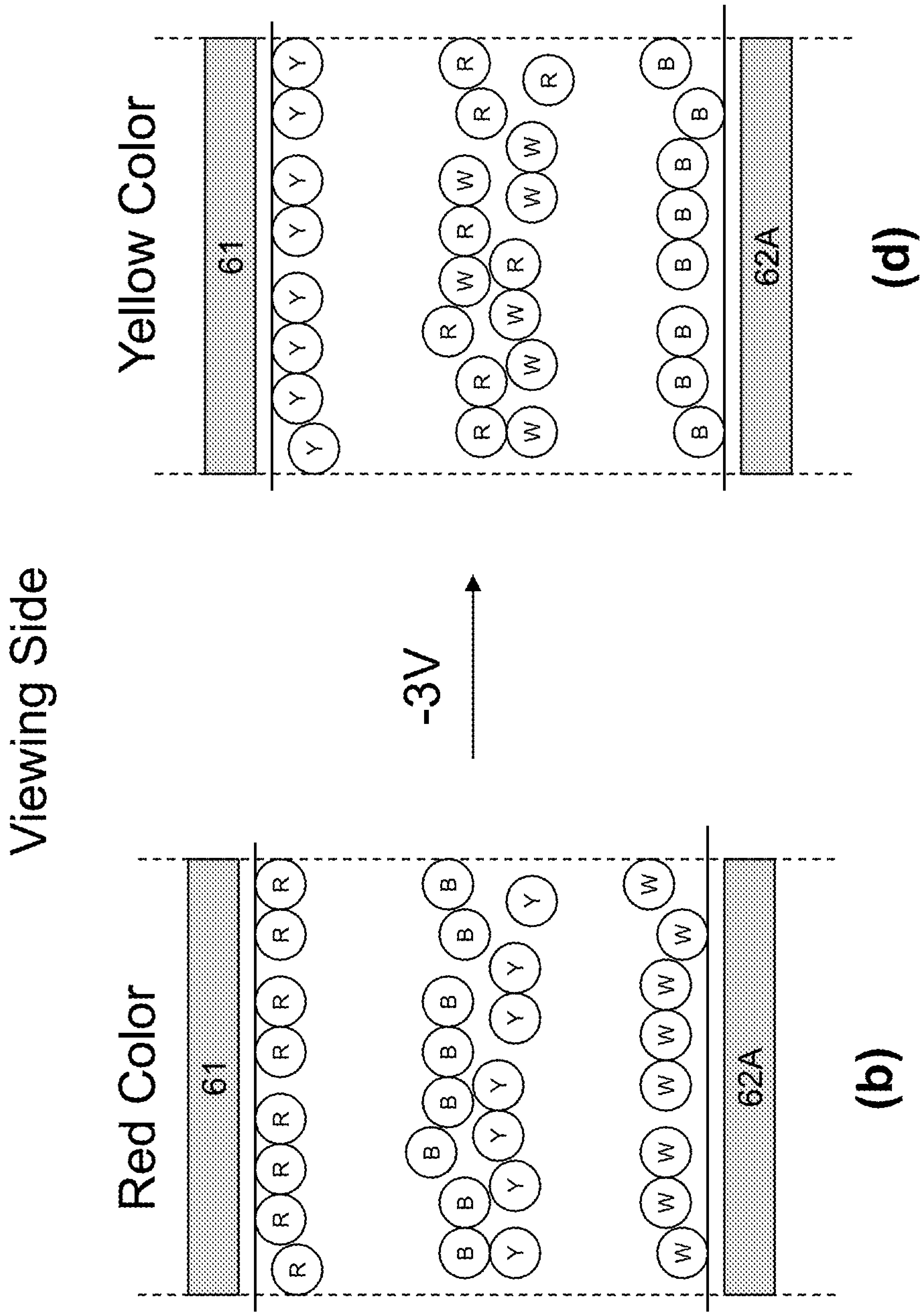


Figure 6-3

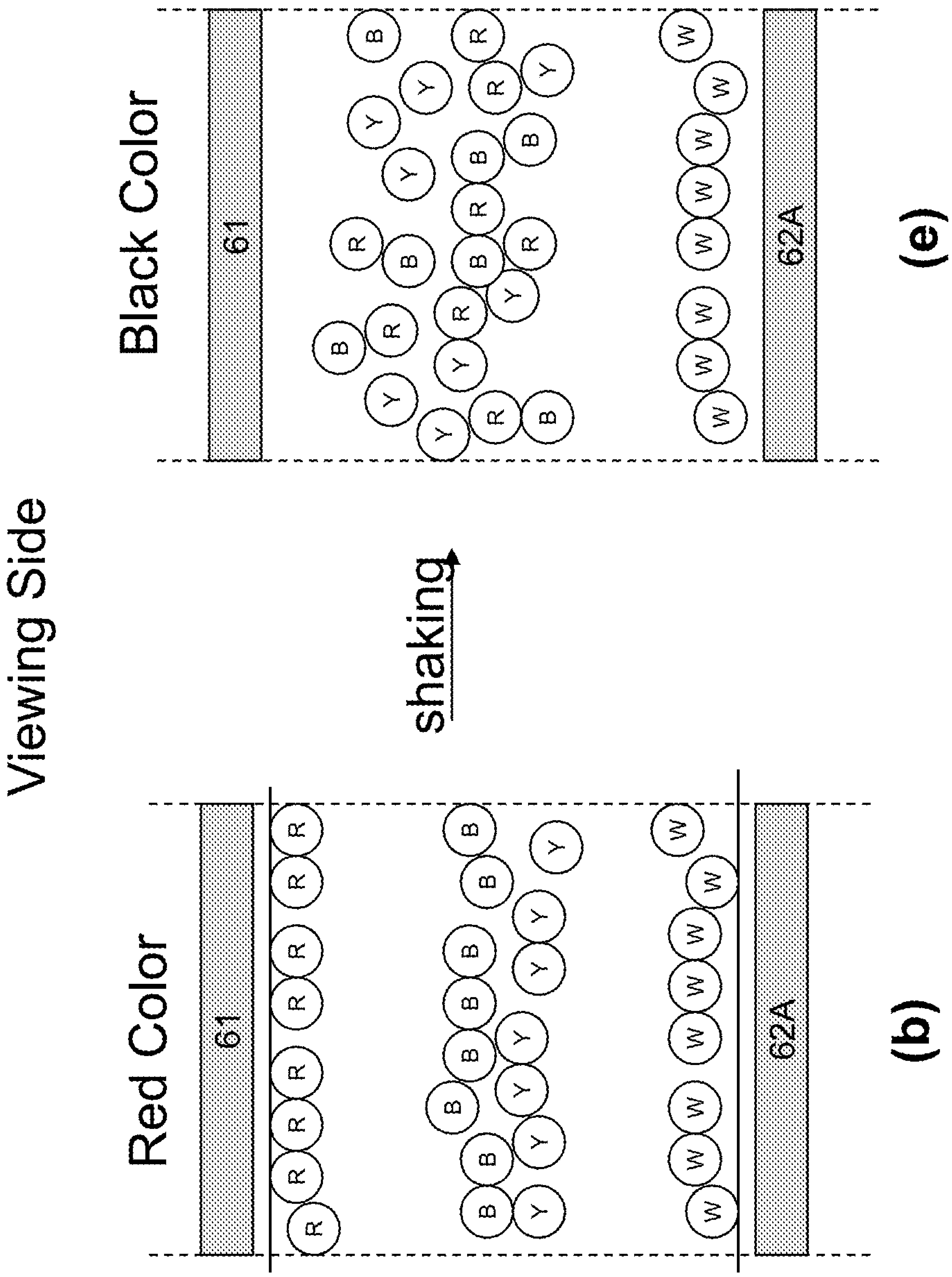


Figure 6-4

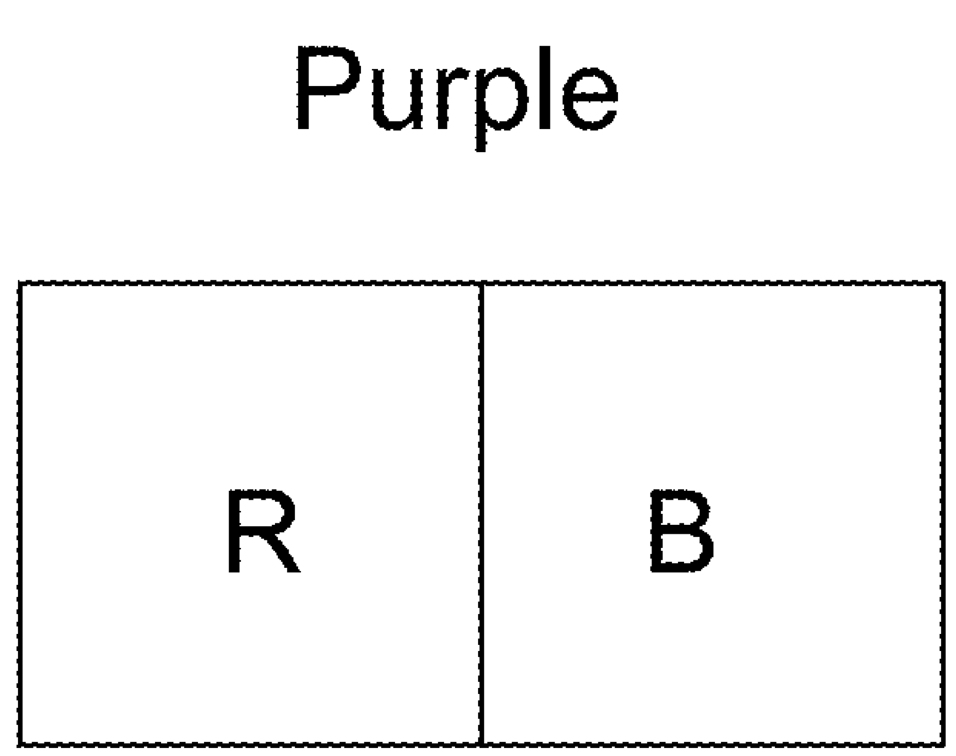


Fig. 7A

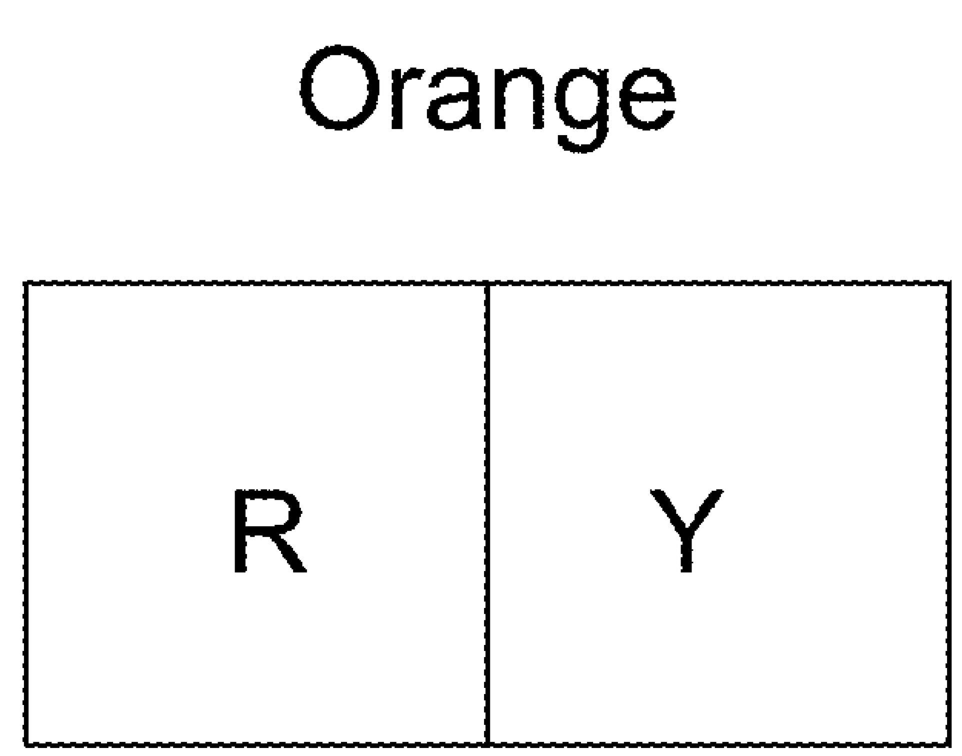


Fig. 7B

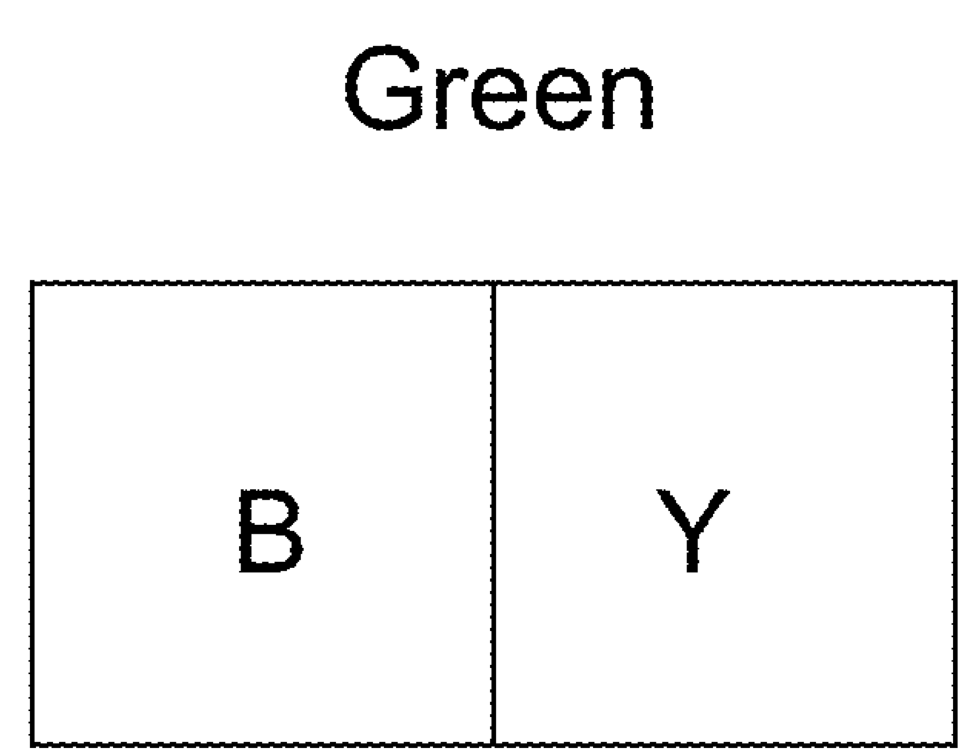


Fig. 7C

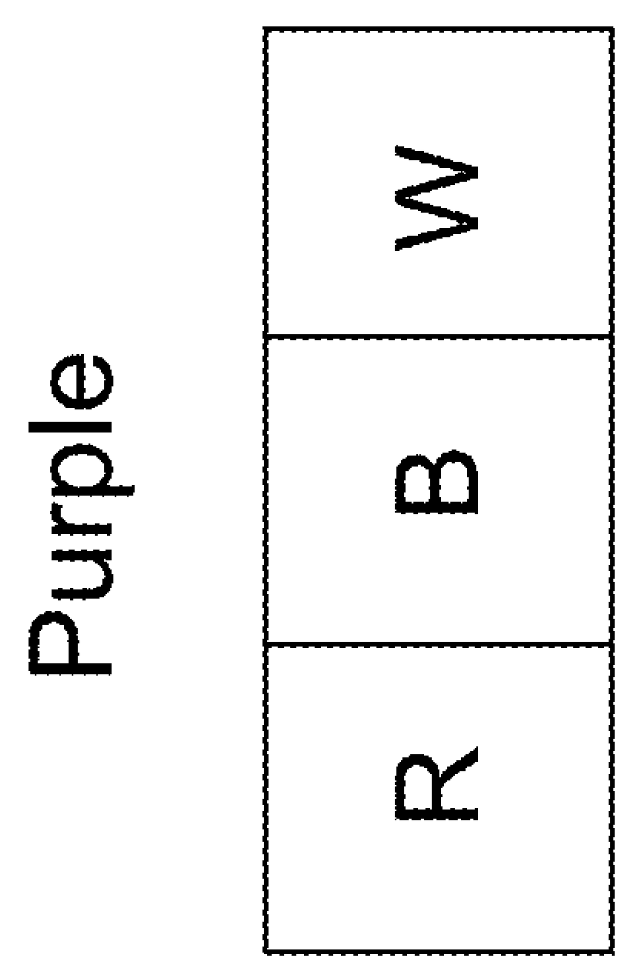


Fig. 8A

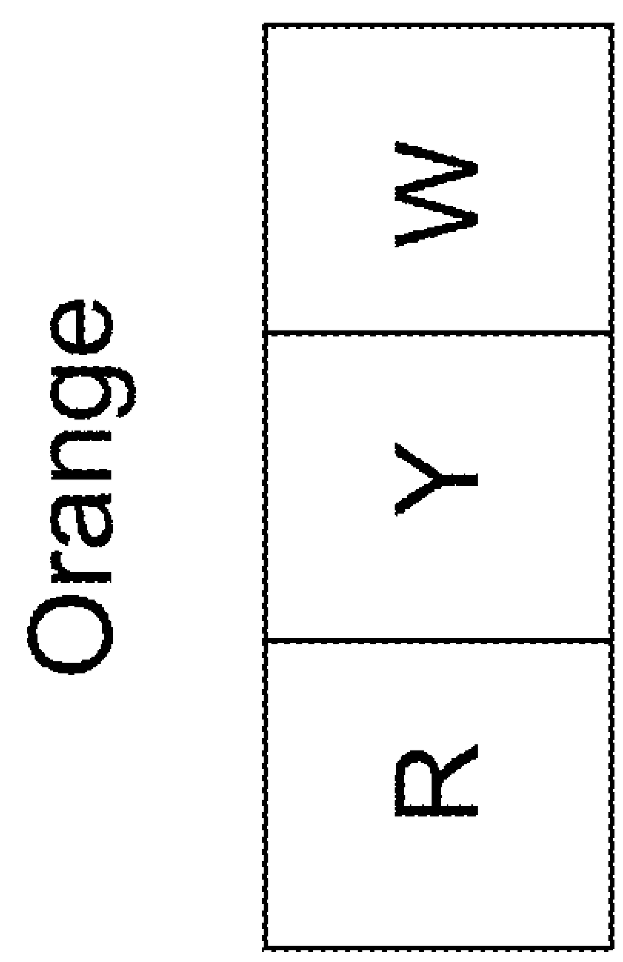


Fig. 8B

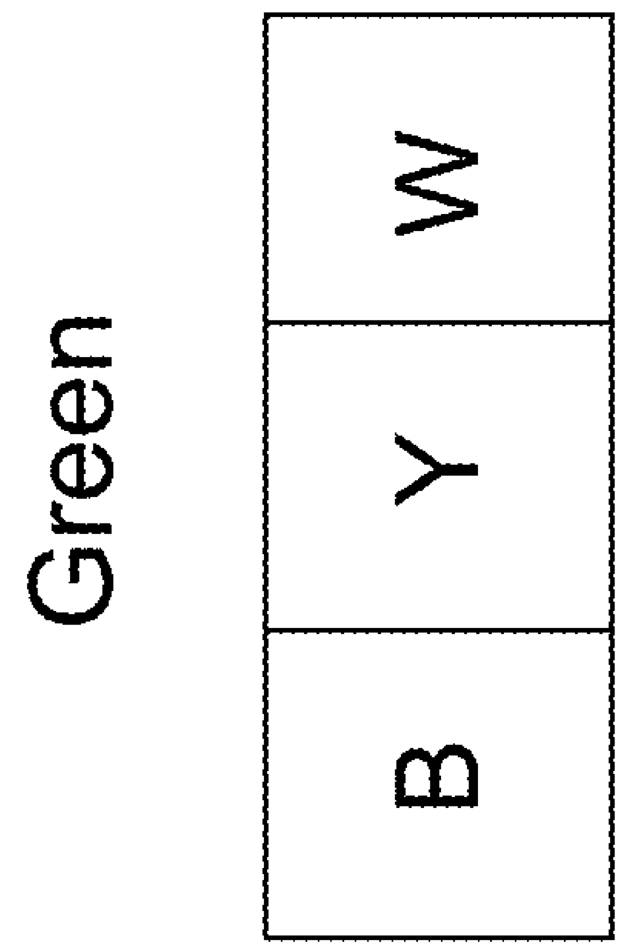


Fig. 8C

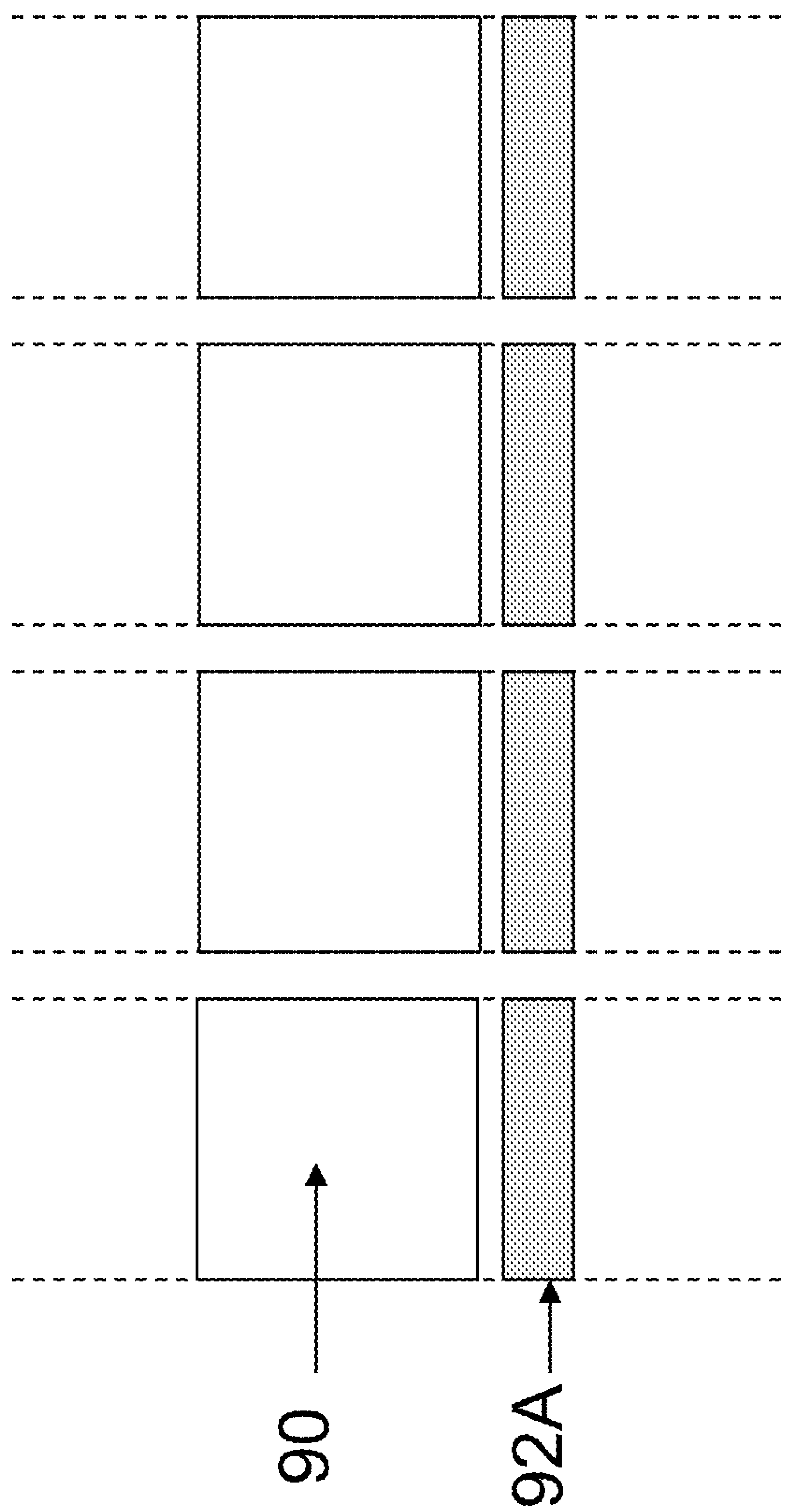


Figure 9A

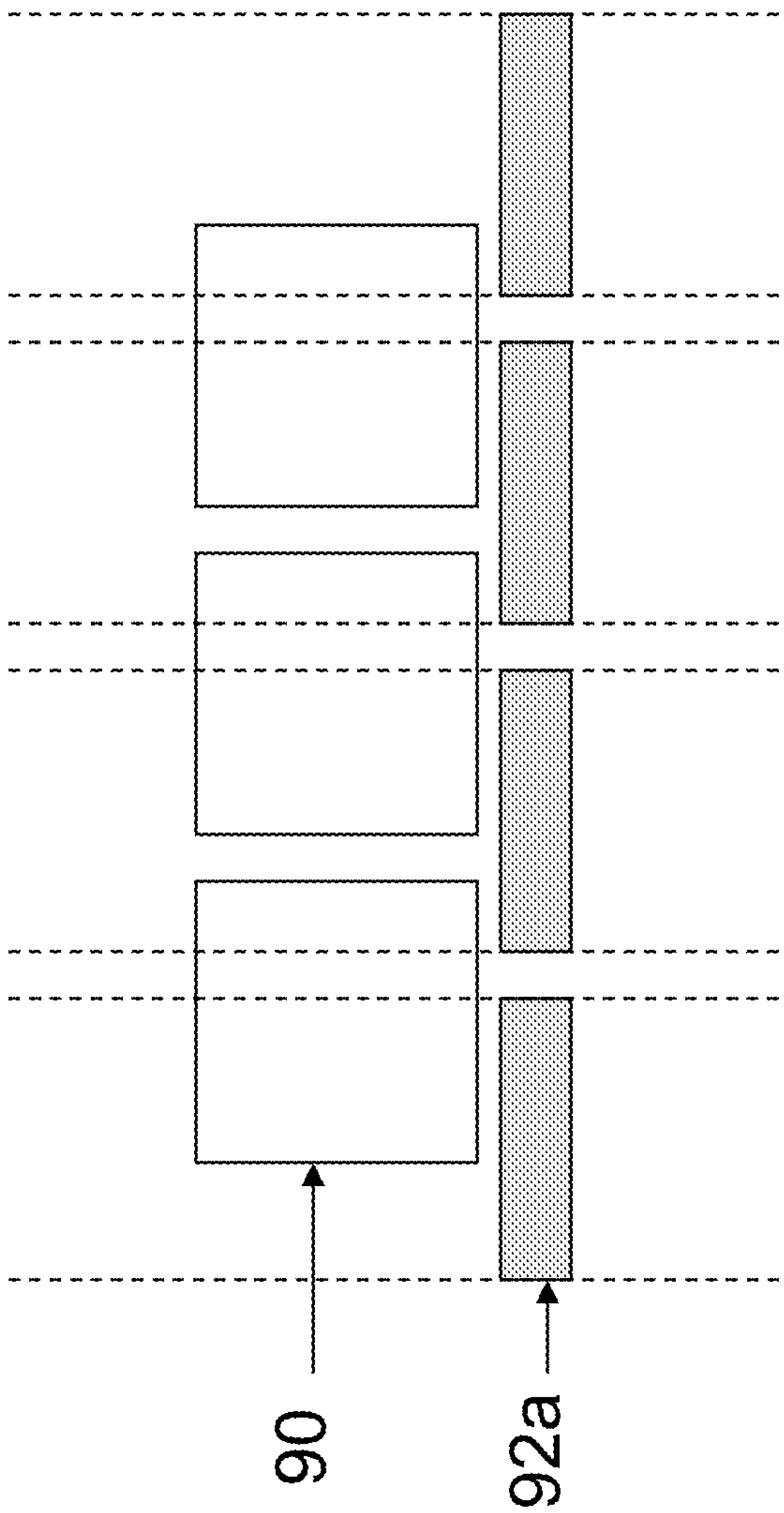


Figure 9B

COLOR DISPLAY DEVICE

REFERENCE TO RELATED APPLICATIONS

This application is a continuation of copending application Ser. No. 14/596,160, filed Jan. 13, 2015 (Publication No. 2015/0198858), which claims benefit of Application Ser. No. 61/927,418, filed Jan. 14, 2014. The entire contents of these applications are incorporated by reference in their entirety.

BACKGROUND OF INVENTION

The present invention is directed to a full color display device in which each pixel can display multiple high-quality color states, and an electrophoretic fluid for such an electrophoretic display.

In order to achieve a color display, color filters are often used. The most common approach is to add color filters on top of black/white sub-pixels of a pixellated display to display the red, green and blue colors. When a red color is desired, the green and blue sub-pixels are turned to the black state so that the only color displayed is red. When a green color is desired, the red and blue sub-pixels are turned to the black state so that the only color displayed is green. When a blue color is desired, the green and red sub-pixels are turned to the black state so that the only color displayed is blue. When the black state is desired, all three-sub-pixels are turned to the black state. When the white state is desired, the three sub-pixels are turned to red, green and blue, respectively, and as a result, a white state is seen by the viewer.

The biggest disadvantage of such a technique is that since each of the sub-pixels has a reflectance of about one third of the desired white state, the white state is fairly dim. To compensate this, a fourth sub-pixel may be added which can display only the black and white states, so that the white level is doubled at the expense of the red, green or blue color level (where each sub-pixel is only one fourth of the area of the pixel). Brighter colors can be achieved by adding light from the white pixel, but this is achieved at the expense of color gamut to cause the colors to be very light and unsaturated. A similar result can be achieved by reducing the color saturation of the three sub-pixels. Even with this approach, the white level is normally substantially less than half of that of a black and white display, rendering it an unacceptable choice for display devices, such as e-readers or displays that need well readable black-white brightness and contrast.

SUMMARY OF INVENTION

One aspect of the present invention is directed to an electrophoretic display, comprising

(a) a plurality of pixels; and

(b) an electrophoretic fluid in which a first type of particles, a second type of particles, a third type of particles and a fourth type of particles are dispersed in a solvent or solvent mixture and the first and second types of particles carry a high level of charge and are oppositely charged and the third and fourth types of particles carry a low level of charge and are oppositely charged,

wherein each of the pixels is capable of displaying at least five different color states.

In one embodiment, the first and second type of articles are of the white and red colors, respectively. In one embodiment, the third and fourth types of particles are of the blue and green colors, respectively. In one embodiment, each of the pixels is capable of displaying white, red, green, blue and black color states. In another embodiment, each of the pixels is capable of displaying yellow, magenta and cyan color states.

In one embodiment, the third and fourth types of particles are of the blue and yellow colors, respectively. In one embodiment, each of the pixels is capable of displaying white, red, yellow, blue and black color states. In one embodiment, each of the pixels is capable of displaying green, orange and purple color states.

In one embodiment, the low level of charge is less than about 50% of the high level of charge. In another embodiment, the low level of charge is less than about 75% of the high level of charge.

In one embodiment, the electrophoretic fluid further comprises substantially uncharged neutral buoyancy particles. In another embodiment, the substantially uncharged neutral buoyancy particles are non-charged.

Another aspect of the present invention is directed to a display layer comprising an electrophoretic fluid and having first and second surfaces on opposed sides thereof, the electrophoretic fluid comprising high positive particles, high negative particles, low positive particles and low negative particles, all dispersed in a solvent or solvent mixture, the four type of particles having respectively optical characteristics differing from one another, such that:

(a) application of an electric field which has the same polarity as the high positive particles will cause the optical characteristics of the high positive particles to be displayed at the first surface; or

(b) application of an electric field which has the same polarity as high negative particles will cause the optical characteristic of the high negative particles to be displayed at the first surface; or

(c) once the optical characteristic of the high positive particles is displayed at the first surface, application of an electric field which has the same polarity as low negative particles, but is not strong enough to overcome the attraction force between the high positive particles and the high negative particles, but sufficient to overcome the attraction forces between other oppositely charged particles will cause the optical characteristic of the low negative particles to be displayed at the first surface; or

(d) once the optical characteristic of the high negative particles is displayed at the first surface, application of an electric field which has the same polarity as the low positive particles, but is not strong enough to overcome the attraction force between the high positive particles and the high negative particles, but sufficient to overcome the attraction forces between other oppositely charged particles will cause the optical characteristic of the low positive particles to be displayed at the first surface; or

(e) application of a shaking waveform will cause a fifth optical characteristic to be displayed at the first surface.

In one embodiment of this aspect of the invention, the four types of particles are red, green, blue and white. In another embodiment, the four types of particles are red, yellow, blue and white. In a further embodiment, the four types of particles are cyan, magenta, yellow and white.

In one embodiment, none of the four types of particles is black particles and the fifth optical characteristic is a black color state.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** depicts an electrophoretic display device of the present invention.

FIGS. **2-1** to **2-4** illustrate an example of the present invention.

FIG. **3** shows a shaking waveform.

FIGS. **4**A-**4**C and **5**A-**5**C show how yellow, magenta and cyan color states may be displayed by a display device of FIG. **2**.

FIGS. **6-1** to **6-4** illustrate another example of the present invention.

FIGS. **7**A-**7**C and **8**A-**8**C show how purple, orange and green color states may be displayed by a display device of FIG. **6**.

FIGS. **9**A and **9**B, respectively, demonstrate display cells aligned or unaligned with pixel electrodes.

DETAILED DESCRIPTION

The electrophoretic fluid of the present invention comprises four types of particles dispersed in a dielectric solvent or solvent mixture. For ease of illustration, the four types of pigment particles may be referred to as the first type (**11**), the second type (**12**), the third type (**13**) and the fourth type (**14**) of particles, as shown in FIG. **1**. However, with only four types of pigment particles, a display device utilizing the electrophoretic fluid may display at least five different color states, which leads to a full color display.

Generally, the four types of particles are divided into two groups—high charge group and low charge group. In the two groups of oppositely charged particles, one group carries a stronger charge than the other group. Therefore the four types of pigment particles may also be referred to as high positive particles, high negative particles, low positive particles and low negative particles.

As an example, red particles (R) and white particles (W) may be the first group of oppositely charged particles, and in this group, the red particles are the high positive particles and the white particles are the high negative particles. The blue particles (B) and the green particles (G) may be the second group of oppositely charged particles and in this group, the blue particles are the low positive particles and the green particles are the low negative particles.

In another example, red particles may be the high positive particles; white particles may be the high negative particles; blue particles may be the low positive particles and yellow particles may be the low negative particles.

It is understood that the scope of the invention broadly encompasses particles of any colors as long as the four types of particles have visually distinguishable colors.

For the white particles, they may be formed from an inorganic pigment, such as TiO_2, ZrO_2, ZnO, Al_2O_3, Sb_2O_3, $BaSO_4$, $PbSO_4$ or the like.

For the black particles, if present, they may be formed from CI pigment black 26 or 28 or the like (e.g., manganese ferrite black spinel or copper chromite black spinel) or carbon black. **321** Particles of other colors (non-white and non-black) are independently of a color such as red, green, blue, magenta, cyan or yellow. The pigments for color particles may include, but are not limited to, CI pigment PR 254, PR122, PR149, PG36, PG58, PG7, PB28, PB15:3, PY83, PY138, PY150, PY155 or PY20. Those are commonly used organic pigments described in color index handbooks, "New Pigment Application Technology" (CMC Publishing Co, Ltd, 1986) and "Printing Ink Technology" (CMC Publishing Co, Ltd, 1984). Specific examples include Clariant Hostaperm Red D3G 70-EDS, Hostaperm Pink E-EDS, PV fast red D3G, Hostaperm red D3G 70, Hostaperm Blue B2G-EDS, Hostaperm Yellow H4G-EDS, Novoperm Yellow HR-70-EDS, Hostaperm Green GNX, BASF Irgazine red L 3630, Cinquasia Red L 4100 HD, and Irgazin Red L 3660 HD; Sun Chemical phthalocyanine blue, phthalocyanine green, diarylide yellow or diarylide AAOT yellow.

The non-black and non-white color particles may also be inorganic pigments, such as red, green, blue and yellow pigments. Examples may include, but are not limited to, CI pigment blue 28, CI pigment green 50 and CI pigment yellow 227.

In addition to the colors, the four types of particles may have other distinct optical characteristics, such as optical transmission, reflectance, and luminescence or, in the case of displays intended for machine reading, pseudo-color in the sense of a change in reflectance of electromagnetic wavelengths outside the visible range.

As also shown in FIG. **1**, a display layer utilizing the display fluid of the present invention has two surfaces, a first surface (**17**) on the viewing side and a second surface (**18**) on the opposite side of the first surface (**17**). The display fluid is sandwiched between the two surfaces. On the side of the first surface (**17**), there is a common electrode (**15**) which is a transparent electrode layer (e.g., ITO), spreading over the entire top of the display layer. On the side of the second surface (**18**), there is an electrode layer (**16**) which comprises a plurality of pixel electrodes (**16**A).

The pixel electrodes are described in U.S. Pat. No. 7,046,228, the content of which is incorporated herein by reference in its entirety. It is noted that while active matrix driving with a thin film transistor (TFT) backplane is mentioned for the layer of pixel electrodes, the scope of the present invention encompasses other types of electrode addressing as long as the electrodes serve the desired functions.

Each space between two dotted vertical lines in FIG. **1** denotes a pixel. As shown, each pixel has a corresponding pixel electrode. An electric field is created for a pixel by the potential difference between a voltage applied to the common electrode and a voltage applied to the corresponding pixel electrode.

The percentages of the four types of particles in the fluid may vary. For example, one type of particles may take up 0.1% to 50%, preferably 0.5% to 15%, by volume of the electrophoretic fluid.

The solvent in which the four types of particles are dispersed is clear and colorless. It preferably has a low viscosity and a dielectric constant in the range of about 2 to about 30, preferably about 2 to about 15 for high particle mobility. Examples of suitable dielectric solvent include hydrocarbons such as isopar, decahydronaphthalene (DECALIN), 5-ethylidene-2-norbornene, fatty oils, paraffin oil, silicon fluids, aromatic hydrocarbons such as toluene, xylene, phenylxylylethane, dodecylbenzene or alkylnaphthalene, halogenated solvents such as perfluorodecalin, perfluorotoluene, perfluoroxylene, dichlorobenzotrifluoride, 3,4,5-trichlorobenzotrifluoride, chloropentafluorobenzene, dichlorononane or pentachlorobenzene, and perfluorinated solvents such as FC-43, FC-70 or FC-5060 from 3M Company, St. Paul Minn., low molecular weight halogen containing polymers such as poly(perfluoropropylene oxide) from TCI America, Portland, Oreg., poly(chlorotrifluoroethylene) such as Halocarbon Oils from Halocarbon Product Corp., River Edge, N.J., perfluoropolyalkylether such as Galden from Ausimont or Krytox Oils and Greases K-Fluid Series from DuPont, Del., polydimethylsiloxane based silicone oil from Dow-corning (DC-200).

In one embodiment, the charge carried by the "low charge" particles may be less than about 50%, or about 5%

to about 30%, of the charge carried by the "high charge" particles. In another embodiment, the "low charge" particles may be less than about 75%, or about 15% to about 55%, the charge carried by the "high charge" particles. In a further embodiment, the comparison of the charge levels as indicated applies to two types of particles having the same charge polarity.

The charge intensity may be measured in terms of zeta potential. In one embodiment, the zeta potential is determined by Colloidal Dynamics AcoustoSizer IIM with a CSPU-100 signal processing unit, ESA EN# Attn flow through cell (K:127). The instrument constants, such as density of the solvent used in the sample, dielectric constant of the solvent, speed of sound in the solvent, viscosity of the solvent, all of which at the testing temperature (25° C.) are entered before testing. Pigment samples are dispersed in the solvent (which is usually a hydrocarbon fluid having less than 12 carbon atoms), and diluted to between 5-10% by weight. The sample also contains a charge control agent (Solsperse 17000®, available from Lubrizol Corporation, a Berkshire Hathaway company; "Solsperse" is a Registered Trade Mark), with a weight ratio of 1:10 of the charge control agent to the particles. The mass of the diluted sample is determined and the sample is then loaded into the flow through cell for determination of the zeta potential.

The magnitudes of the "high positive" particles and the "high negative" particles may be the same or different. Likewise, the magnitudes of the "low positive" particles and the "low negative" particles may be the same or different.

It is also noted that in the same fluid, the two groups of high-low charge particles may have different levels of charge differentials. For example, in one group, the low positively charged particles may have a charge intensity which is 30% of the charge intensity of the high positively charged particles and in another group, the low negatively charged particles may have a charge intensity which is 50% of the charge intensity of the high negatively charged particles.

The charge polarities and levels of charge for the particles may be tuned, according to the method described in US Publication No. 2014-0011913, the contents of which are incorporated herein by reference in its entirety.

It is also noted that the four types of particles may have different particle sizes. For example, smaller particles may have a size which ranges from about 50 nm to about 800 nm. Larger particles may have a size which is about 2 to about 50 times, and more preferably about 2 to about 10 times, the sizes of the smaller particles.

EXAMPLE 1

This example is demonstrated in FIG. **2**. The fluid in this example has red, green, blue and white pigment particles. The red particles (R) carry a high positive charge, the white particles (W) carry a high negative charge, the blue (B) particles carry a low positive charge and the green particles (G) carry a low negative charge.

In FIG. **2-1**, when a high negative voltage potential difference (e.g., −15V) is applied to a pixel, the white particles (W) are pushed to the common electrode (**21**) side and the red particles (R) are pulled to the pixel electrode (**22**A) side. The blue (B) and green (G) particles, due to their lower charge level, move slower than the higher charged white and red particles and therefore they stay in the middle of the pixel, with green particles above the blue particles. As a result, the white color is seen at the viewing side (State (a) in FIG. **2-1**).

In FIG. **2-1**, when a high positive voltage potential difference (e.g., +15V) is applied to the pixel, the particle distribution would be opposite of State (a) and as a result, the red color is seen at the viewing side (State (b) in FIG. **2-1**).

In FIG. **2-2**, when a lower positive voltage potential difference (e.g., +3V) is applied to the pixel in State (a) (that is, driven from the white state), the white particles (W) move towards the pixel electrode (**22**A) while the red particles (R) move towards the common electrode (**21**). When they meet while moving, because of their strong attraction to each other, they stop moving and remain in the middle of the pixel. In other words, the electric field generated by the low positive voltage potential difference is not strong enough to separate the white and red particles.

However, the electric field is strong enough to separate the lower charged blue and green particles and also strong enough to overcome the attraction forces between the oppositely charged high-low particle pairs (white/blue and red/green). As a result, the lower charged (positive) blue particles (B) move all the way to the common electrode (**21**) side (i.e., the viewing side) and the lower charged (negative) green particles (G) move to the pixel electrode (**22**A) side. Consequently, the blue color is seen at the viewing side (State (c) in FIG. **2-2**).

In FIG. **2-3**, when a lower negative voltage potential difference (e.g., −3V) is applied to the pixel in State (b) (that is, driven from the red state), the red particles (R) move towards the pixel electrode (**22**A) while the white particles (W) move towards the common electrode (**21**). When the white and red particles meet, because of their strong attraction to each other, they stop moving and remain in the middle of the pixel. In other words, the electric field generated by the low negative voltage potential difference is not strong enough to separate the white and red particles.

However, the electric field is strong enough to separate the lower charged blue and green particles and also strong enough to overcome the attraction forces between the oppositely charged high-low particle pairs (white/blue and red/green). As a result, the lower charged (negative) green particles (G) move all the way to the common electrode side (i.e., the viewing side) and the lower charged (positive) blue particles (B) move to the pixel electrode side. Consequently, the green color is seen at the viewing side (State (d) in FIG. **2-3**).

In FIG. **2-4**, State (e), a black color is seen from the viewing side. This may be achieved by applying a shaking waveform when a pixel is in the red color state (State (b)) to cause the red, green and blue particles to be mixed in the upper part of the pixel, leading to the black state to be seen at the viewing side.

A shaking waveform consists of repeating a pair of opposite driving pulses for many cycles. For example, the shaking waveform may consist of a +15V pulse for 20 msec and a −15V pulse for 20 msec and such a pair of pulses is repeated for 50 times. The total time of such a shaking waveform would be 2000 msec (see FIG. **3**).

In practice, there may be at least 10 repetitions (i.e., ten pairs of positive and negative pulses).

After the shaking waveform is applied, the optical state would be from a mixture of the particles, seen to be black in the present example.

Each of the driving pulse in the shaking waveform is applied for not exceeding 50% (or not exceeding 30%, 10% or 5%) of the driving time required from the full white state to the full red state in the example. For example, if it takes 300 msec to drive a pixel from a full white state to a red yellow state or vice versa, the shaking waveform may consist of positive and negative pulses, each applied for not more than 150 msec. In practice, it is preferred that the pulses are shorter.

It is also noted that the lower voltage potential difference applied to reach the color States (c) and (d) may be about 5% to about 50% of the full driving voltage potential difference required to drive the pixel from the red state to the white state or from the white state to the red state.

While Example 2 demonstrates the possibility of a pixel exhibiting black, white, red, green or blue color state, the present invention also provides the possibility for a pixel to exhibit yellow, magenta or cyan color state.

In FIGS. **4**A-**4**C, each pixel has two sub-pixels. In FIG. **4**A, a yellow state is displayed when one sub-pixel displays a red color and the other sub-pixel displays a green color. In FIG. **4**B, one sub-pixel displays a red color and the other sub-pixel displays a blue color, leading the pixel to display a magenta state. In FIG. **4**C, a pixel displays a cyan color state while one of the sub-pixels displays a blue color and the other sub-pixel displays a green color.

To display a brighter yellow, magenta or cyan color state, a pixel may consist of three sub-pixels. This is shown in FIGS. **5**A-**5**C wherein a third sub-pixel is added, which third sub-pixel displays only the white color state.

EXAMPLE 2

This example is demonstrated in FIGS. **6-1** to **6-4**. The fluid in this example has red, yellow, blue and white pigment particles. The red particles (R) carry a high positive charge, the white particles (W) carry a high negative charge, the blue (B) particles carry a low positive charge and the yellow particles (Y) carry a low negative charge.

In FIG. **6-1**, when a high negative voltage potential difference (e.g., −15V) is applied to a pixel, the white particles (W) are pushed to the common electrode (**61**) side and the red particles (R) are pulled to the pixel electrode (**62**A) side. The blue (B) and yellow (Y) particles, due to their lower charge level, move slower than the higher charged white and red particles and therefore they stay in the middle of the pixel, with yellow particles above the blue particles. As a result, the white color is seen at the viewing side (State (a) in FIG. **6-1**).

Also in FIG. **6-1**, when a high positive voltage potential difference (e.g., +15V) is applied to the pixel, the particle distribution would be opposite of State (a) and as a result, the red color is seen at the viewing side (State (b) in FIG. **6-1**).

In FIG. **6-2**, when a lower positive voltage potential difference (e.g., +3V) is applied to the pixel in State (that is, driven from the white state), the white particles (W) move towards the pixel electrode (**62**A) while the red particles (R) move towards the common electrode (**61**). When they meet while moving, because of their strong attraction to each other, they stop moving and remain in the middle of the pixel. In other words, the electric field generated by the low positive voltage potential difference is not strong enough to separate the white and red particles.

However, the electric field is strong enough to separate the lower charged blue and yellow particles and also strong enough to overcome the attraction forces between the oppositely charged high-low particle pairs (white/blue and red/yellow). As a result, the lower charged (positive) blue particles (B) move all the way to the common electrode (**61**) side (i.e., the viewing side) and the lower charged (negative) yellow particles (Y) move to the pixel electrode (**62**A) side. Consequently, the blue color is seen at the viewing side (State (c) in FIG. **6-2**).

In FIG. **6-3**, when a lower negative voltage potential difference (e.g., −3V) is applied to the pixel in State (b) (that is, driven from the red state), the red particles (R) move towards the pixel electrode (**62**A) while the white particles (W) move towards the common electrode (**61**). When the white and red particles meet, because of their strong attraction to each other, they stop moving and remain in the middle of the pixel. In other words, the electric field generated by the low negative voltage potential difference is not strong enough to separate the white and red particles.

However, the electric field is strong enough to separate the lower charged blue and yellow particles and also strong enough to overcome the attraction forces between the oppositely charged high-low particle pairs (white/blue and red/yellow). As a result, the lower charged (negative) yellow particles (Y) move all the way to the common electrode side (i.e., the viewing side) and the lower charged (positive) blue particles (B) move to the pixel electrode side. Consequently, the yellow color is seen at the viewing side (State (d) in FIG. **6-3**).

In FIG. **6-4**, a black color is seen from the viewing side. This may be achieved by applying a shaking waveform when a pixel is in the red color state (State (b)), leading to the black color state to be seen at the viewing side (State (e) in FIG. **6-4**).

Similarly as described in Example 2, the lower voltage potential difference applied to reach the color States (c) and (d) may be about 5% to about 50% of the full driving voltage potential difference required to drive the pixel from the red state to the white state or from the white state to the red state.

While Example 2 demonstrates the possibility of a pixel exhibiting black, white, red, yellow or blue color state, the present invention also provides the possibility for a pixel to exhibit purple, orange or green color state.

In FIGS. **7**A-**7**C, each pixel has two sub-pixels. In FIG. **7**A, a purple state is displayed when one sub-pixel displays a red color and the other sub-pixel displays a blue color. Likewise, in FIG. **7**B, one sub-pixel displays a red color and the other sub-pixel displays a yellow color, leading the pixel to display an orange state. In FIG. **7**C, a pixel displays a green color state while one of the sub-pixels displays a blue color and the other sub-pixel displays a yellow color.

To display a brighter purple, orange or green color state, a pixel may consist of three sub-pixels. This is shown in FIGS. **8**A-**8**C wherein a third sub-pixel is added, which third sub-pixel displays only the white color state.

Although in the two examples, particles of specific colors are demonstrated to be utilized, in practice as stated above, the particles carrying a high positive charge, or a high negative charge, or a low positive charge or a low negative charge may be of any colors. All of these variations are intended to be within the scope of this application. For example, the four types of particles may be cyan, magenta, yellow and white.

In a further aspect of the present invention, the fluid may further comprise substantially uncharged neutral buoyancy particles.

The term "substantially uncharged" refers to the particles which are either uncharged or carry a charge which is less than 5% of the average charge carried by the charged particles. In one embodiment, the neutral buoyancy particles are non-charged.

The term "neutral buoyancy" refers to particles which do not rise or fall with gravity. In other words, the particles would float in the fluid between the two electrode plates. In one embodiment, the density of the neutral buoyancy particles may be the same as the density of the solvent or solvent mixture in which they are dispersed.

The concentration of the substantially uncharged neutral buoyancy particles in the display fluid is preferably in the range of about 0.1 to about 10% by volume, more preferably in the range of about 0.1 to about 5% by volume.

The substantially uncharged neutral buoyancy particles may be formed from a polymeric material. The polymeric material may be a copolymer or a homopolymer.

Examples of the polymeric material for the substantially uncharged neutral buoyancy particles may include, but are not limited to, polyacrylate, polymethacrylate, polystyrene, polyaniline, polypyrrole, polyphenol and polysiloxane. Specific examples of the polymeric material may include, but are not limited to, poly(pentabromophenyl methacrylate), poly(2-vinylnapthalene), poly(naphthyl methacrylate), poly(alpha-methylstyrene), poly(N-benzyl methacrylamide) and poly(benzyl methacrylate).

More preferably, the substantially uncharged neutral buoyancy particles are formed from a polymer which is not soluble in the solvent of the display fluid, and also has a high refractive index. In one embodiment, the refractive index of the substantially uncharged neutral buoyancy particles is different from that of the solvent or solvent mixture in which the particles are dispersed. However, typically the refractive index of the substantially uncharged neutral buoyancy particles is higher than that of the solvent or solvent mixture. In some cases, the refractive index of the substantially uncharged neutral buoyancy particles may be above 1.45.

In one embodiment, the materials for the substantially uncharged neutral buoyancy particles may comprise an aromatic moiety.

The substantially uncharged neutral buoyancy particles may be prepared from monomers through polymerization techniques, such as suspension polymerization, dispersion polymerization, seed polymerization, soap-free polymerization, emulsion polymerization or physical method, including inverse emulsification-evaporation process. The monomers are polymerized in the presence of a dispersant. The presence of the dispersant allows the polymer particles to be formed in a desired size range and the dispersant may also form a layer physically or chemically bonded to the surface of the polymer particles to prevent the particles from agglomeration.

The dispersant preferably has a long chain (of at least eight atoms), which may stabilize the polymer particles in a hydrocarbon solvent. Such dispersants may be an acrylate-terminated or vinyl-terminated macromolecule, which are suitable because the acrylate or vinyl group can co-polymerize with the monomer in the reaction medium.

One specific example of the dispersant is acrylate terminated polysiloxane (Gelest, MCR-M17, MCR-M22),

Another type of suitable dispersants is polyethylene macromonomers, as shown below:

$$CH_3—[—CH_2]_n—CH_2O—C(=O)—C(CH_3)=CH_2$$

The backbone of the macromonomer may be a polyethylene chain and the integer "n" may be 30-200. The synthesis of this type of macromonomers may be found in Seigou Kawaguchi et al, Designed Monomers and Polymers, 2000, 3, 263.

If the fluid system is fluorinated, the dispersants are then preferably also fluorinated.

Alternatively, the substantially uncharged neutral buoyancy particles may also be formed from a core particle coated with a polymeric shell and the shell may be formed, for example, from any of the polymeric material identified above.

The core particle may be of an inorganic pigment such as TiO_2, ZrO_2, ZnO, Al_2O_3, CI pigment black 26 or 28 or the like (e.g., manganese ferrite black spinel or copper chromite black spinel), or an organic pigment such as phthalocyanine blue, phthalocyanine green, diarylide yellow, diarylide AAOT yellow, and quinacridone, azo, rhodamine, perylene pigment series from Sun Chemical, Hansa yellow G particles from Kanto Chemical, and Carbon Lampblack from Fisher, or the like.

In the case of core-shell substantially uncharged neutral buoyancy particles, they may be formed by a microencapsulation method, such as coacervation, interfacial polycondensation, interfacial cross-linking, in-suit polymerization or matrix polymerization.

The size of the substantially uncharged neutral buoyancy particles is preferably in the range of about 100 nanometers to about 5 microns.

In one embodiment of this aspect of the present invention, the substantially uncharged neutral buoyancy particles added to the fluid may have a color substantially the same visually to the color of one of the four types of charged particles. For example, in a display fluid, there may be charged red, green, blue and white particles and substantially uncharged neutral buoyancy particles, and in this case, the substantially uncharged neutral buoyancy particles may be red, green, blue or white.

In another embodiment, the substantially uncharged neutral buoyancy particles may have a color substantially different from the color of either one of the four types of charged particles.

The presence of the substantially uncharged neutral buoyancy particles in the fluid increases reflection of incident light, thus also improving the contrast ratio, especially if they are formed from a reflective material.

The image stability may also be improved by the addition of the substantially uncharged neutral buoyancy particles in the four particle fluid system. The substantially uncharged neutral buoyancy particles can fill in the gaps resulted from the charged particles being over packed on the surface of an electrode under an electrical field, thus preventing the charged particles from settling due to the gravitational force.

In addition, if the substantially uncharged neutral buoyancy particles are white, they may enhance the reflectivity of the display. If they are black, they may enhance the blackness of the display.

In any case, the substantially uncharged neutral buoyancy particles do not affect the driving behavior of the four types of charged particles in the fluid.

The electrophoretic fluid as described above is filled in display cells. The display cells may be cup-like microcells as described in U.S. Pat. No. 6,930,818, the content of which is incorporated herein by reference in its entirety. The display cells may also be other types of micro-containers, such as microcapsules, microchannels or equivalents, regardless of their shapes or sizes. All of these are within the scope of the present application.

As shown in FIGS. **9**A and **9**B, the display cells (**90**), in the present invention, and the pixel electrodes (**92**A) may be aligned or un-aligned.

The term "about", throughout this application, is intended to mean ±5% of an indicated value.

While the present invention has been described with reference to the specific embodiments thereof, it should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation, materials, compositions, processes, process step or steps, to the objective, spirit and scope of the present invention. All such modifications are intended to be within the scope of the claims appended hereto.

The invention claimed is:

1. An electrophoretic display comprising:

(a) a plurality of pixels; and

(b) an electrophoretic medium comprising a first type of particle having a first optical characteristic and a positive zeta potential, a second type of particle having a second optical characteristic and a negative zeta potential, a third type of particle having a third optical characteristic and a positive zeta potential lower than that of the first type of particle, and a fourth type of particle having a fourth optical characteristic and a negative zeta potential lower than that of the second type of particle, the first, second, third and fourth optical characteristics being different from one another and none of them being a black color,

wherein each of the pixels is capable of displaying the first, second, third and fourth optical characteristics and a black color.

2. The display of claim **1** wherein two of the first, second, third and fourth optical characteristics are white and red.

3. The display of claim **2** wherein the remaining two of the first, second, third and fourth optical characteristics are blue and either green or yellow.

4. The display of claim **1** wherein the zeta potential of the third and fourth types of particles is less than about 75 per cent of the zeta potential of the first and second types of particles respectively.

5. The display of claim **4** wherein the zeta potential of the third and fourth types of particles is less than about 50 per cent of the zeta potential of the first and second types of particles respectively.

6. The display of claim **1** wherein the electrophoretic medium further comprises substantially uncharged neutral buoyancy particles.

7. The electrophoretic display of claim **1** having a viewing surface and wherein:

(a) application to the electrophoretic medium of a first electric field having a polarity driving the first type of particle towards the viewing surface will cause the first optical characteristic to be displayed at the viewing surface;

(b) application to the electrophoretic medium of a second electric field having a polarity driving the second type of particle towards the viewing surface will cause the second optical characteristic to be displayed at the viewing surface;

(c) once the first optical characteristic is displayed at the viewing surface, application to the electrophoretic medium of a third electric field having the same polarity as the second electric field but a smaller magnitude will cause the fourth optical characteristic to be displayed at the viewing surface; and

(d) once the second optical characteristic is displayed at the viewing surface, application to the electrophoretic medium of a fourth electric field having the same polarity as the first electric field but a smaller magnitude will cause the third optical characteristic to be displayed at the viewing surface.

8. The electrophoretic display of claim **7** wherein application of a shaking waveform to the electrophoretic medium will cause a black color to be displayed at the viewing surface.

9. The display of claim **8** wherein the zeta potential of the third and fourth types of particles is less than about 75 per cent of the zeta potential of the first and second types of particles respectively.

10. The display of claim **9** wherein the zeta potential of the third and fourth types of particles is less than about 50 per cent of the zeta potential of the first and second types of particles respectively.

11. A method of driving an electrophoretic medium, the medium having a viewing surface and comprising a first type of particle having a first optical characteristic and a positive zeta potential, a second type of particle having a second optical characteristic and a negative zeta potential, a third type of particle having a third optical characteristic and a positive zeta potential lower than that of the first type of particles, and a fourth type of particle having a fourth optical characteristic and a negative zeta potential lower than that of the second type of particle, the first, second, third and fourth optical characteristics being different from one another and none of them being a black color, the method comprising, in any order:

(a) applying to the electrophoretic medium a first electric field having a polarity driving the first type of particle towards the viewing surface, thereby causing the first optical characteristic to be displayed at the viewing surface;

(b) applying to the electrophoretic medium a second electric field having a polarity driving the second type of particle towards the viewing surface, thereby causing the second optical characteristic to be displayed at the viewing surface;

(c) once the first optical characteristic is displayed at the viewing surface, applying to the electrophoretic medium a third electric field having the same polarity as the second electric field but a smaller magnitude, thereby causing the fourth optical characteristic to be displayed at the viewing surface;

(d) once the second optical characteristic is displayed at the viewing surface, applying to the electrophoretic medium a fourth electric field having the same polarity as the first electric field but a smaller magnitude, thereby causing the third optical characteristic to be displayed at the viewing surface; and

(e) applying a shaking waveform to the electrophoretic medium, thereby causing a black color to be displayed at the viewing surface.

12. The method of claim **11** wherein two of the first, second, third and fourth optical characteristics are white and red.

13. The method of claim **12** wherein the remaining two of the first, second, third and fourth optical characteristics are blue and either green or yellow.

14. The method of claim **11** wherein the magnitudes of the third and fourth electric fields are from about 5 to about 50 per cent of the magnitudes of the second and first electric fields respectively.

* * * * *